BODY COMPOSITION AND MUSCLE FUNCTION:
Examining Leg Lean Mass and its Relation to Muscle Function in Healthy Athletes and Athletes with Previous Anterior Cruciate Ligament Injury

A DISSERTATION
SUBMITTED TO THE FACULTY OF THE
UNIVERSITY OF MINNESOTA
BY

Christiana Joy Raymond-Pope

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

Doctor of Philosophy

Donald R. Dengel, Ph.D., Advisor

May 2019

ACKNOWLEDGEMENTS

It is with great pleasure to have been given the opportunity to prepare this dissertation under the advisement of Dr. Donald Dengel, Ph.D. and my committee members, Dr. Tyler Bosch, Ph.D., Dr. John Fitzgerald, Ph.D., Dr. Christopher Lundstrom, Ph.D., and Dr. Sarah Greising, Ph.D. Thank you, Dr. Dengel, for your mentorship and advice, as well as for providing me with multiple research, writing, and teaching opportunities throughout the duration of my graduate career. Your time and willingness to meet to answer all of my questions (and at times they were many) and to discuss my research direction and future goals has always spoken volumes to me. Thank you, Dr. Bosch, for your mentorship in the design and implementation of the research studies included in this dissertation, in addition to the valuable statistical lessons you have provided to me. Thank you, Dr. Fitzgerald, for your valuable guidance and assistance in analyzing, interpreting, and understanding jump mechanography data and discussing its applications within the context of this dissertation's studies. Thank you, Dr. Lundstrom, for providing me with opportunities within each of your courses to dive into the literature pertinent to my dissertation. These opportunities allowed me to gain greater insight into the fields of training, rehabilitation, and ACL injury and subsequently apply this information to my dissertation research/writing. Thank you, Dr. Greising, for your willingness to serve as Chair of my committee, for your time and helpful feedback when meeting, and for allowing me the opportunity to do research in a post-doctoral fellowship position within your laboratory. I am very much looking forward to beginning this research and collaborating with others in the lab on various projects.

DEDICATION

To my wonderful husband and family for their continuous support, encouragement, and advice. To my husband, Zachary, for his helpful insights and encouraging words throughout the duration of my graduate degree and in the production of this dissertation. Thank you, Zachary, for your unconditional support, patience, and positivity. To my father for demonstrating an incredible work ethic and a love of learning, and to my mother for her unconditional encouragement and positivity. To my siblings for their amazing support and advice, and for serving as inspiring examples of leadership, hard work, and perseverance through challenges faced.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF ABBREVIATIONS

ACL: Anterior cruciate ligament

ACLR: Anterior cruciate ligament reconstruction

ACLR Athlete: Athlete with prior anterior cruciate ligament reconstruction

BMC: Bone mineral content

BMD: Bone mineral density

BMI: Body mass index

%BF: Percent body fat

CMJ: Countermovement jump

CT: Computed tomography

DVJ: Drop vertical jump

DXA: Dual X-ray absorptiometry

FM: Fat mass

FFM: Fat-free mass

INV: Involved leg

LM: Lean mass

MRI: Magnetic resonance imaging

NINV: Non-involved leg

RFD: Rate of force development

ROI: Region of interest

RTS: Return to sport

SJ: Squat jump

CHAPTER 1. INTRODUCTION

Total and regional (i.e., arms, legs) body composition and lower extremity muscle strength and force assessments are commonly used within sport performance settings to cross-sectionally and longitudinally examine: (a) training and nutritional interventions' effectiveness (Ackland et al., 2012; Hart et al., 2015); (b) the contribution of contralateral (i.e., between-leg) lean mass and strength asymmetries to injury/reinjury risk (Bell et al., 2014; Bishop et al., 2018; Hewit et al., 2012; Impellizzeri et al., 2007); (c) training and rehabilitation progress; and (d) readiness to return to sport (RTS) following rehabilitation (Newton et al., 2006). Therefore, when utilized concurrently, body composition, strength, and force production measurements provide insight into optimizing sport performance and reducing lower extremity injury and reinjury risk (e.g., primary and secondary anterior cruciate ligament [ACL] injury) in healthy and previously injured athletes, respectively.

To date, researchers have employed computed tomography (CT) and magnetic resonance imaging (MRI) to quantify upper-leg muscle cross-sectional area (CSA) and volume (MV) (Akagi et al., 2014; Denadai et al., 2016; Konishi et al. 2011), while others (Bell et al., 2014; Jordan et al., 2015; Krzykala & Leszczynski, 2015) have used dual X-ray absorptiometry (DXA) to measure lower extremity lean mass, and contralateral upper- and lower-leg lean mass asymmetries, in the standard frontal view. Additionally, researchers have utilized open (e.g., isokinetic dynamometry) and closed (e.g., vertical jumping) kinetic chain tests to examine athletes' muscle-specific and explosive (i.e., time-restricted force production) strength. Notably, however, most current literature has reported examining lean mass and the preceding muscle function assessments independently, with fewer studies assessing these measures in combination. Specifically, among healthy and previously ACL injured-athletes, these studies have examined the relationship between: (a) quadriceps and hamstring CSA/MV and isokinetic knee extensor/flexor strength; and (b) DXA-assessed leg lean mass and force produced during vertical jumping. These studies have reported mixed correlations between CSA/MV and isokinetic peak torque (Akagi et al., 2014; Denadai et al., 2016; Masuda et al., 2003) but have noted a direct relationship between DXA-measured leg lean mass and force production (Bell et al., 2014; Jordan et al., 2015; Stephenson et al., 2015).

It is also noteworthy that even fewer studies have examined the relationship between contralateral lean mass and muscle function *asymmetries* in healthy and previously ACL-injured athletes—despite the utility that examining this association may have for lower extremity injury risk assessment (Bishop et al., 2018). Further, no studies to date have used DXA to assess upper-leg compartmental (i.e., anterior/posterior) lean mass's relationship with muscle-specific and explosive strength. To enable compartmental assessment, our laboratory developed and demonstrated the accuracy and reliability of using a lateral "segmentation method" for assessing *ipsilateral* (same-leg) upper-leg compartmental lean mass in the lateral view using a GE Lunar iDXA scanner (Raymond et al., 2017). However, as literature has reported differences in body composition estimates across DXA scanners produced by the three main manufacturers (GE Healthcare Lunar, Hologic Inc., and Norland Inc.) and scanner models made by one manufacturer (e.g., GE Lunar Prodigy vs. iDXA; Toombs et al., 2012; Tothill et al., 1994a, 1994b), assessing the lateral scanning method's accuracy using another DXA scanner model is warranted.

Using the lateral segmentation method to examine upper-leg compartmental lean mass's relationship with isokinetic knee extensor/flexor strength and force production measured via vertical jumping may offer distinct advantages over lean mass examinations completed in the frontal view. Briefly, the lateral segmentation method may better assess the presence of location-specific upper-leg lean mass deficits and how these deficits contribute to strength and force production asymmetries. Given that strength and force production asymmetries have been implicated in primary and secondary ACL injury mechanisms, the greater insight the lateral segmentation method might provide could facilitate the development of more effective training and rehabilitation programs to prevent primary and secondary ACL injury. Therefore, this dissertation's purpose was to: (a) examine the lateral segmentation method's measurement accuracy on another DXA scanner model; and (b) evaluate DXA-measured leg lean mass's relationship with strength and force production in healthy and previously ACL-injured athletes.

This dissertation's specific aims were as follows:

1. Evaluate the agreement of fat, lean, and bone mass measurements obtained using the novel lateral scanning method in comparison to these measurements obtained in the standard frontal scanning view using a Hologic Horizon A DXA scanner.

   a. *Hypothesis:* Total, fat, and lean masses, bone mineral content, and bone mineral density measured by the Hologic Horizon A scanner in the standard frontal position and novel lateral position will not significantly differ within individuals.

2. Assess the association of lean mass measured using the lateral segmentation DXA scanning method and muscle-specific and explosive strength measures and further compare this method to traditional frontal view lean mass measurements.

   a. *Hypotheses*: Upper-leg compartmental (i.e., anterior/posterior) lean mass measured via DXA will be strongly associated with isokinetic knee flexor and extensor strength—similar to that of total- and upper-leg lean masses. Further, the lateral segmentation method will demonstrate some relation to explosive strength during a jumping task.

3. In a matched case-control study design, (a) examine lean mass, muscle-specific, and explosive strength differences (i) between the involved and non-involved legs of adolescent female athletes approximately one-year post-ACL reconstruction and (ii) between matched legs of ACLR adolescent female athletes and athlete controls; and (b) examine the relationship between lean mass and (i) knee extensor/flexor peak torque and (ii) explosive strength to determine relative muscle functionality in ACLR female athletes' involved and non-involved legs.

   a. *Hypotheses:* Significant lean mass asymmetries will be present between ACLR female athletes' involved and non-involved legs one-year post-reconstruction, and ACLR female athletes will have lower lean mass in each compartment versus controls. Further, ACLR female athletes will produce less strength and force relative to lean mass in both legs versus controls.

This dissertation's second chapter provides a comprehensive review of the existing literature on body composition and functional assessment testing in healthy and previously

ACL injured athletes. ACL injury mechanisms and risk factors are also described, followed by a discussion of the limited research conducted thus far to assess the relationship between lean mass and functional asymmetries contributing to this injury.

The third chapter discusses a study evaluating the agreement of the lateral DXA scanning method—a method previously demonstrated accurate on one DXA scanner model (GE Lunar iDXA)—relative to the standard frontal scanning view for measuring upper-leg composition on another scanner model (Hologic Horizon A).

The fourth chapter reviews an investigation of the association between lower extremity lean mass measured using the lateral segmentation method and (a) isokinetic knee extensor and flexor peak torque and (b) jump height and force production during vertical jump testing in a healthy, college-aged population.

The fifth chapter outlines a study evaluating deficits in leg lean mass, isokinetic knee extensor/flexor peak torque, and explosive strength (i.e., force production) in female adolescent athletes approximately one year following ACL reconstruction versus matched controls. Further, this study will assess the relationship between leg lean mass measured in three regions of interest (ROIs) and muscle-specific strength and force production.

Finally, a summary of each study and pertinent observations are reviewed in chapter six. Future research surrounding the relationship between lean muscle mass and strength/force production is proposed.

CHAPTER 2. REVIEW OF LITERATURE

Introduction

Within the sport performance and rehabilitation settings, body composition evaluations and lower extremity maximal muscle-specific (i.e., quadriceps, hamstrings) and explosive (i.e., time-restricted force production) strength measurements are frequently performed. Although commonly examined separately, these assessment methods used in combination allow sports practitioners and researchers to comprehensively: (a) examine training and nutritional interventions' effectiveness; (b) evaluate contralateral (i.e., inter-limb) lean mass, strength, and force production asymmetries for injury and reinjury risk assessment; (c) monitor rehabilitation progress; and (d) assist with return to sport (RTS) decision-making following injury and rehabilitation (Ackland et al., 2012; Bell et al., 2014; Grindem et al., 2016; Impellizzeri et al., 2007; Jordan et al., 2015; Newton et al., 2006).

Anterior cruciate ligament (ACL) knee injuries are one of the most severe lower extremity injuries suffered by athletes, with multiple modifiable (e.g., muscle strength imbalances, hamstring flexibility, etc.) and non-modifiable (e.g., sex, age, anatomy, etc.) risk factors identified thus far (Beynnon et al., 2014; Hewett et al., 2005; Joseph et al., 2013; Renstrom et al., 2008). Therefore, the relationship between lower extremity body composition and muscle strength/force may be particularly important in evaluating athletes' primary and secondary ACL injury risk. However, while regional lean mass measurements allow contralateral asymmetries to be detected, which may underlie strength asymmetries and increase injury risk (Bell et al., 2014; Bishop et al., 2018), lower extremity muscle-specific and explosive strength assessments have been more commonly used to assess athletes' contralateral asymmetries—reported to increase athletes' ACL injury risk

(Bell et al., 2014; Konishi et al., 2012; Kyrtsis et al., 2016; Grindem et al., 2016; Wellsandt et al., 2017).

To date, most studies in healthy and previously ACL-injured/reconstructed athletes (hereafter referred to as "ACLR athletes") have used either: (a) computed tomography (CT) or magnetic resonance imaging (MRI) to examine the relationship between muscle cross-sectional area (CSA) or volume (MV) and muscle-specific strength measured via isokinetic/isometric testing (Akagi et al., 2014; Denadai et al., 2016; Konishi et al., 2007; Konishi et al., 2011; Konishi et al., 2012; Masuda et al., 2003); or (b) dual X-ray absorptiometry (DXA) to evaluate the association between lean mass and force production measured via vertical jumping (Bell et al., 2014; Jordan et al., 2015). Using DXA, these investigators have only examined healthy and ACLR athletes' contralateral lower extremity lean mass asymmetries in the standard frontal scanning view—assessing, most often, the relationship between asymmetries in contralateral lean mass and force production. Notably, however, recent research has advocated for a more detailed body composition analysis method capable of improving the understanding of how muscle-specific lean mass asymmetries contribute to dysfunctional lower extremity biomechanics and ACL injury/reinjury risk (Bishop et al., 2018; Shultz & Schmitz, 2018). Recently, Raymond et al. (2017) examined and reported DXA's accuracy when measuring upper-leg compartmental (i.e., anterior/posterior) composition in the lateral scanning view. This lateral DXA scanning method is pertinent as it allows for compartmental upper-leg muscle-specific lean mass asymmetries to be measured *ipsilaterally* (i.e., within the same leg)—increasing researchers' capability to conduct more detailed investigations examining healthy and ACLR athletes' relative muscle functionality (i.e., strength/force per unit of lean mass) and the mechanisms possibly underlying primary and secondary ACL injury.

The following literature review first describes body composition and lower extremity strength assessments commonly used within the sport performance and rehabilitation settings, followed by a discussion of theorized risk factors and underlying mechanisms contributing to primary and secondary ACL injury. Finally, the currently understood relationship between lower extremity lean muscle mass and (a) muscle-specific strength and (b) force production in healthy and ACLR athletes is discussed.

Utility of DXA in the Sport Performance & Rehabilitation Settings

While CT, MRI, and DXA are commonly employed within clinical settings, DXA is also used within the sport performance and rehabilitation settings due to DXA's greater practicality and feasibility (Ackland et al., 2012). For example, compared to CT and MRI, DXA's use has multiple advantages, including: a quick scan time (3-7 min.); low ionizing radiation (vs. CT); low cost; immediate results; non-invasive nature; and low required technician expertise (Kim et al., 2002; Bilsborough et al., 2014; Tothill et al., 1995). Additionally, the typical 70-cm CT gantry aperture (i.e., entry) diameter and 90-cm MRI scanner tunnel may leave little room for a larger individual, perhaps also making individuals feel claustrophobic, thus limiting these devices' use in the sport performance and rehabilitation settings (Modica et al., 2011). Another advantage of DXA is its capability to segment the body's upper and lower extremities using automatically- and manually-created regions of interest (ROIs). Importantly, segmented body composition analyses have demonstrated accuracy and reliability when cross-sectionally and longitudinally assessing athletes' region-specific body composition (Bilsborough et al., 2014; Buehring et al. 2014; Burkhart et al., 2009; Hart et al., 2015; Nana et al., 2014; Pineau et al., 2009; Santos et al., 2010). Therefore, given DXA's capabilities, sport practitioners and researchers regard DXA as a *practical gold standard* criterion body composition assessment method in the sport performance setting (Stewart & Sutton, 2012).

Within the sport performance and rehabilitation settings, DXA has most often been used to: (a) cross-sectionally and longitudinally examine athletes' total and regional fat and lean masses; (b) evaluate training and nutritional programs' effectiveness; and (c) assess contralateral lower extremity lean mass asymmetries (Bell et al., 2014; Bosch et al., 2018; Dengel et al., 2017). Notably, DXA's examination of the effects of fat and lean masses, and their distribution in particular body regions, on sport performance is important. Specifically, fat mass is non-functional mass, with greater amounts possibly hindering sport performance and increasing injury risk. Conversely, lean mass represents functional mass, with increased lean mass shown to improve strength, power, and physical performance (Barlow et al., 2015; Bosch et al., 2014; Bosch et al., 2018; Dengel et al., 2017; Stewart et al., 2001). Thus, DXA-assessed body composition measurements can be used to modify training programs to increase lean mass and reduce fat mass in a manner consistent with the athlete's sport requirements. DXA is also commonly used to examine lower extremity lean mass asymmetries potentially contributing to strength asymmetries which may increase athletes' injury risk (e.g., ACL injury) (Bell et al., 2014; Jordan et al., 2015; Krzykala & Leszczynski, 2015)—perhaps informative for monitoring athletes' training/rehabilitation progress. However, while researchers have primarily examined lower extremity *contralateral* lean mass asymmetries using DXA in the standard frontal view, *ipsilateral* upper-leg compartmental lean mass asymmetry assessments are lacking but may allow for more in-depth (i.e., location-specific) examinations of asymmetries contributing to athletes' functional performance deficits and potential ACL injury risk.

Although one study (Raymond et al., 2017) has examined the accuracy and reliability of a lateral DXA scanning method to examine ipsilateral upper-leg compartmental lean mass using a GE Lunar iDXA scanner, replicating this method on other manufacturers' scanner models is necessary. Replication is particularly important when considering research has noted differences in body composition estimates between DXA scanners built by the three primary DXA manufacturers—GE Healthcare, Hologic Inc., and Norland Inc. (Bazzocchi et al., 2016)—and across DXA scanner models produced by the same manufacturer (e.g., GE Lunar Prodigy vs. GE Lunar iDXA) (Genton et al., 2005; Hull et al., 2009; Tothill et al., 1994a; Tothill et al., 1994b; Tothill et al., 2001; Toombs et al., 2012). These researchers postulated that the proprietary algorithms used in different manufacturers' post-scan analysis software, in addition to differences in scanning geometry (i.e., pencil-, fan-, and narrow fan-beam) across scanner models, as major contributory factors to these measurement differences (Bazzocchi et al., 2016; Tothill et al., 2001; Van Loan et al., 1995). Therefore, evaluating the lateral scanning method's accuracy on another DXA scanner is important.

This lateral DXA scanning method's accuracy on different scanner models would provide rationale for this method's more widely-spread use within the sport performance and rehabilitation settings. Notably, researchers have suggested more detailed body composition assessments are needed to examine how body composition—particularly lean mass—may influence primary and secondary ACL injury risk (Bishop et al., 2018; Shultz & Schmitz, 2018). Therefore, the ability to quantify upper-leg compartmental lean mass and relate these measurements to lower extremity muscle-specific and explosive strength measures would provide a more in-depth evaluation of relative muscle functionality. Further, accurate assessment of these relationships may provide greater insight into how lean mass and strength/force asymmetries comprehensively affect primary and secondary ACL injury risk, while also aiding clinicians in the development of more effective strength training/rehabilitation programs to reduce these asymmetries (Bishop et al., 2018).

Lower Extremity Functional Assessments Used in Healthy & ACLR Athletes

While body composition assessment is important for optimizing athletes' sport performance and preventing injuries possibly resulting from contralateral asymmetries, implementing lower extremity functional assessments is also necessary to examine normalized strength/force and potential asymmetries in these measures that may translate to sport performance. Further, if the preceding measures are used in combination, assessing the relationship between lean mass and strength/force would allow for relative muscle functionality assessment. However, prior to reviewing research that has thus far examined these lean mass-strength/force relationships in healthy and ACLR athletes, it is necessary to first review the most commonly employed lower extremity functional assessment methods used in the sport performance and rehabilitation settings.

Recent literature has reported several lower extremity functional assessments used to cross-sectionally and longitudinally: (a) monitor athletes' training and rehabilitation progress; (b) examine contralateral and ipsilateral lower extremity strength and force production asymmetries potentially increasing athletes' injury risk (e.g., ACL injury); (c) identify the location and extent of muscle weakness following injury and reconstruction; and (d) evaluate athletes' readiness to RTS following rehabilitation (Ackland et al., 2012; Grindem et al., 2016; Holsgaard-Larsen et al., 2014; Impellizzeri et al., 2007; Newton et al., 2006; Wellsandt et al., 2017). These functional assessment methods can be categorized as one of two types: (a) open kinetic chain (e.g., isokinetic dynamometry); and (b) closed kinetic chain (e.g., jump mechanography). Open kinetic chain tests involve examining the strength of specific muscles (i.e., muscle-specific strength) moving across one joint, while closed kinetic chain tests involve energy transfer across multiple joints using multiple muscle groups, therefore assessing athlete's degree of explosiveness (i.e., time-restricted force production; hereafter termed 'force') (Iossofidou et al., 2005). Notably, the different muscle and joint mechanics assessed during open and closed kinetic testing allow for the examination of different muscle characteristics, including: (a) maximal muscle-specific (e.g., knee extensor/flexor) strength; and (b) force generated with or without stretch-shortening cycle incorporation (Iossofidou et al., 2005).

Isokinetic dynamometry has historically been considered the preferred technique to measure normalized muscular forces (i.e., Nm/kg) of antagonistic muscle groups (e.g., quadriceps/hamstrings) (Baltzopoulos et al., 2012; Pua et al., 2008). Given isokinetic dynamometry's capability to isolate specific muscles (e.g., quadriceps, hamstrings) during movement in one plane and to provide reliable strength (i.e., peak torque) measurements (Feiring et al., 1990), this method has also been commonly used to evaluate athletes' contralateral upper-leg strength asymmetries (e.g., right vs. left quadriceps)—asymmetries which may increase primary and secondary ACL injury risk (Aagaard et al., 1998; Baltzopoulos & Brodie, 1989; Grindem et al., 2016). Strength measurements made during contralateral assessments are typically used to calculate a limb symmetry index [LSI = (involved leg's peak torque/non-involved leg's peak torque) x 100], with contralateral symmetry values >85% desired for primary and secondary ACL injury risk prevention (Neeter et al., 2006; Wiggins et al., 2016). Notably, however, despite isokinetic dynamometry's reliability, this assessment method is limited in its biomechanical specificity to sport performance (Pua et al., 2008), with testing typically performed at velocities below that required for optimal sport performance.

While isokinetic dynamometry has been used since the 1960s, researchers have more recently been interested in the use of closed kinetic chain assessment methods in both healthy and ACLR athletes, with a common method being jump mechanography (Impellizzeri et al., 2007). Unlike isokinetic dynamometry, jump mechanography is a multi-joint dynamic assessment method—involving the transfer of energy across all lower extremity joints (i.e., ankle, knee, hip)—that incorporates various vertical jump types performed on force plates. These jumps include the drop vertical jump (DVJ), countermovement jump (CMJ), and squat jump (SJ). Briefly, jump mechanography provides measurements of jump height (i.e., perceivable outcome) and each leg's peak force production and rate of force development (RFD) (Impellizzeri et al., 2007). Jump mechanography's capability to provide these measurements has resulted in this method's use when evaluating athletes' contralateral force production asymmetries and assessing athletes' readiness to RTS (Cormie et al., 2009; Eagles et al., 2015). Although this assessment method does not directly examine *muscle-specific* force production—potentially masking muscle-specific strength deficits (e.g., quadriceps, hamstrings)—this method demonstrates greater biomechanical specificity to sport movements by allowing for asymmetry evaluation during multi-joint movements (Impellizzeri et al., 2007).

Overall, open and closed kinetic chain assessment methods are important to employ in the sport performance and rehabilitation settings for healthy and ACLR athletes (Davies et al., 2018). In fact, research has suggested that no single strength measure can adequately provide insight into all injury mechanisms during any given movement (Cronin & Hansen, 2005). Thus, multiple methods should be used concurrently.

Risk Factors & Underlying Mechanisms for ACL Injury

Research has reported the lower extremity as the most commonly injured site in athletes, with the knee and ankle joints having the greatest injury rates (Roos et al., 2015). Anterior cruciate ligament knee injuries are among the most severe lower extremity injuries in athletes, with up to 80% of these injuries occurring without contact (McNair et al., 1990; Joseph et al., 2013; Renstrom et al., 2008). Literature has indicated that female athletes have a 2- to 6-fold greater primary ACL tear incidence compared to males while participating in sex-comparable sports requiring jumping and rapid directional changes (e.g., basketball, soccer) (Beynnon et al., 2014; Ford et al., 2003a; Ford et al., 2003b; Joseph et al., 2013; Paterno et al., 2012). Given the high ACL injury incidence, many investigations have sought to characterize ACL injury risk factors and mechanisms. Prior to discussing these, however, a review of the ACL's function is needed to provide context.

The ACL is a knee ligament extending from the proximal anterior portion of the tibia to the posteromedial portion of the lateral femoral condyle (Kweon et al., 2013). Mechanically, the ACL and quadriceps muscles are antagonists at knee-flexion angles less than 45° (Markolf et al., 1978), while the hamstring muscles act as ACL agonists at these angles to protect the ACL (Alkjaer et al., 2012; Bryant et al., 2008; Osternig et al., 1995). Together with the hamstring muscles, the ACL's purpose is to: stabilize the knee during internal tibial rotation and knee valgus (i.e., medial collapse of the knee); prevent knee joint hyperextension; and prevent excessive anterior tibial translation (i.e., forward shift of the tibia during quadriceps muscle contraction)—a movement which increases ACL tear risk. The ACL's stabilization of the knee is paramount, particularly as jumping and changing directions during high-intensity sports expose the knee to high amounts of force, which may cause the ACL to tear when these forces are greater than the ACL can resist (Boden et al., 2000; Heijne & Werner, 2010; Li et al., 1999). Importantly, researchers using video analysis have observed ACL injuries to occur primarily during a non-contact event when the athlete is decelerating, laterally pivoting, and/or landing (Boden et al., 2000; Olsen et al., 2004). Specifically, this research has observed ACL injury risk is greatest during deceleration when: (a) the leg is in or near full extension (0-20° of flexion) as the foot makes ground contact; (b) the femur is flexed, adducted, and internally rotated; (c) the tibia is externally rotated; and (d) the ankle is everted—particularly detrimental when the athlete's body weight is shifted over the involved leg (Alentorn-Geli et al., 2009; Ford et al., 2003a; Ford et al., 2003b; Griffin et al., 2000; Hewett et al., 2006a; Silvers & Mandelbaum, 2007).

Primary ACL Injury

'Primary ACL injury' refers to first ACL injury occurrence whereas 'secondary ACL injury' refers to a second ACL injury either of the ipsilateral (involved) or contralateral (non-involved) leg. Numerous studies have examined athletes' modifiable and non-modifiable ACL injury risk factors, reporting the most common to be the female sex, younger age (i.e., adolescent; < 20 years), high activity level, body mass index (BMI), lower extremity muscle strength imbalances, joint laxity, greater hamstring flexibility, and prior ACL injury (Borchers et al., 2009; Murphy et al., 2003; Myer et al., 2008; Silvers & Mandelbaum, 2007; Wiggins et al., 2016). Recently, Hewett et al. (2005; 2016) outlined three primary etiological factors related to the preceding primary and secondary ACL injury risk factors, with these etiological factors being anatomical, biomechanical/neuromuscular, and hormonal in nature. For this review's purposes, only anatomical and biomechanical/neuromuscular factors will be discussed. Moreover, while some ACL injury risk factors and mechanisms overlap between primary and secondary ACL injuries, they differ enough to warrant separate review.

Anatomically, female athletes' major primary ACL injury risk factors include, but are not limited to: (a) higher lateral posterior-inferior tibial slope; (b) smaller femoral intercondylar notch and ACL diameter; and (c) greater hamstring flexibility which reduces knee joint stability (Ford et al., 2003a; Hewett et al., 2006b; Shultz et al., 2015; Silvers & Mandelbaum, 2007). Notably, knee joint stability has been reported as a key anatomical determinant of primary ACL injury. In fact, female athletes' greater hamstring flexibility and strength deficits (relative to quadriceps strength; termed 'quadriceps dominance') and decreased co-contraction and co-activation of the hamstring and quadriceps muscles have been shown to increase knee joint laxity and decrease knee joint stiffness, thus reducing knee joint stability (Chappell et al., 2012; Hewett et al., 2005; Hewett et al., 2006a; Hewett et al., 2006b; Hewett et al., 2016; Shultz et al., 2012; Uhorchak et al., 2003; White et al., 2003).

Another etiological factor contributing to primary ACL injury risk includes dysfunctional biomechanics and neuromuscular control—factors considered modifiable via neuromuscular training (Hewett et al., 2000; Hewett et al., 2005; Hewett et al., 2016). In the research and rehabilitation settings, three-dimensional (3D) motion capture analysis has been used in conjunction with different vertical jump types, particularly the DVJ, on force plates to identify dysfunctional movement patterns and joint angles which may predict future primary ACL injury (Hewett et al., 2005; Paterno et al., 2010). For example, in a prospective cohort study, Hewett et al. (2005) noted female athletes who went on to suffer a future primary ACL injury (versus athletes who did not) demonstrated the following within the ACL-injured leg during the DVJ's landing phase: (a) smaller knee flexion angle (10.5°; $p<0.05$); (b) greater knee abduction (i.e., valgus) angle (8°; $p<0.05$); (c) 2.5 times greater knee abduction moment ($p<0.001$); and (d) 20% higher vertical ground reaction force ($p<0.05$).

Although the preceding anatomical and neuromuscular factors have been shown to contribute to primary ACL injury, particularly among female athletes, these factors (particularly muscle strength imbalances) also play a role in secondary ACL injury.

Secondary ACL Injury

Athletes' secondary ACL injury rates are as high as 25% and 30% within 12 and 24 months, respectively, following RTS clearance (Paterno et al., 2010; Paterno et al., 2012; Wiggins et al., 2016). Importantly, not only have athletes been reported to reinjure the same leg, but contralateral injury is also common. In a recent systematic review and meta-analysis, Wiggins et al. (2016) reported secondary ACL injury rates of 23% post-RTS in athletes < 25 years of age, with ipsilateral and contralateral reinjury and injury rates of 10% and 12%, respectively. Researchers have hypothesized the higher contralateral leg's secondary ACL injury incidence to be due to several factors, including: (a) persisting primary ACL risk factors; (b) muscle strength/force asymmetries at the time of RTS; and (c) dysfunctional biomechanical movement patterns and neuromuscular control that increase loading on the contralateral leg while protecting the reconstructed leg (Hewett et al., 2005; Leys et al., 2012; Schmitt et al., 2012; Wiggins et al., 2016). Notably, studies assessing secondary ACL injury risk factors have primarily *separately* examined athletes' contralateral lower extremity asymmetries in: (a) muscle-specific strength; (b) jump mechanography-measured force production; and (c) muscle mass and neuromuscular function—each reviewed below.

Muscle-Specific Strength. Isokinetic and isometric assessments have been most frequently used following athletes' ACL reconstruction to evaluate contralateral (i.e., right vs. left quadriceps) muscle-specific strength asymmetries (Grindem et al., 2016; Newton et al., 2006; Schmitt et al., 2012). Specifically, studies examining contralateral quadriceps isokinetic strength at 6- and 12-months post-ACL reconstruction have reported average asymmetries of 23% and 14%, respectively (Andersen et al., 2002; Cardone et al., 2004; McHugh et al., 2002; Risberg & Holm, 2009), with minimal contralateral hamstring asymmetries (i.e., ≤10%) reported (Kvist, 2004; Lepley, 2015). Using isometric testing, Schmitt et al. (2012) reported 44% (i.e., 24/55) of ACLR athletes at the time of RTS demonstrated contralateral quadriceps strength deficits >15% (range = 30-84%)—values greater than the <10-15% asymmetry cutoff recommended for athletes' successful RTS (Adams et al., 2012; Schmitt et al., 2012). Therefore, these studies suggest quadriceps strength asymmetry—indicating quadriceps weakness—as a primary impairment in ACLR athletes up to 2 years following ACL reconstruction (Schmitt et al., 2012), with these asymmetries associated with increased secondary ACL injury risk (Grindem et al., 2016).

Force Production. More recently, researchers have employed jump mechanography to examine contralateral force asymmetries that may increase secondary ACL injury risk—comparing these force asymmetries to the 10-15% cutoff value recommended as part of RTS testing guidelines, and the value above which asymmetries are considered abnormal (Adams et al., 2012; Impellizzeri et al., 2007; Schmitt et al., 2012). In an earlier study, Paterno et al. (2007) observed female athletes 2 years post-ACL reconstruction landed with approximately 15% more force on the non-involved leg during a DVJ ($p<0.001$) while the involved leg demonstrated lower ($p=0.03$) force production during the DVJ's takeoff phase. More recently, Paterno et al. (2011) examined ACLR male and female (age range = 10-25 yrs.) athletes' peak vertical ground reaction force during the DVJ's landing phase at the time of RTS. Observations indicated significant peak vertical ground reaction force deficits in the ACLR athletes' involved leg versus the non-involved leg and both legs of controls (all $p<0.002$). The preceding studies' researchers and others (Hewett et al., 2016) suggested these observations to provide evidence for increased dependence upon the contralateral leg as a compensatory mechanism following ACL reconstruction, perhaps increasing the contralateral leg's secondary ACL injury risk.

Muscle Mass & Neuromuscular Function. It is noteworthy that muscle mass deficits and neuromuscular dysfunction have been hypothesized to underlie strength and force production asymmetries. Specifically, researchers have commonly reported significant asymmetries in quadriceps muscle CSA and MV following ACL reconstruction and rehabilitation—measured via CT and MRI (Arangio et al., 1997; Konishi et al., 2007; Konishi et al., 2011)—indicating quadriceps atrophy (i.e., muscle loss) in the involved leg. More recently, using DXA, Jordan et al. (2015) reported involved leg deficits in total- and upper-leg lean mass measured in the standard total-body frontal view. Additionally, neuromuscular dysfunction in the form of central activation failure (i.e., arthrogenic muscle inhibition [AMI]) has also been reported following ACL reconstruction (Konishi et al., 2002, 2003; Snyder-Mackler et al., 1994). Specifically, AMI decreases motor unit recruitment and firing frequency during voluntary quadriceps contraction to minimize anterior tibial translation and prevent excessive strain on the ACL graft (Baugher et al., 1984; Bryant et al., 2008; Halkjaer-Kristensen & Ingemann-Hansen, 1985). Consequently, AMI may prevent quadriceps strengthening during rehabilitation due to a lack of muscle fiber stimulation—possibly leading to long-term involved leg quadriceps muscle atrophy, weakness, and reduced knee joint stability, which may increase secondary ACL injury risk (Kuenze et al., 2014; Lohmander et al., 2007; Palmieri-Smith et al., 2008).

Taken together, while literature has primarily reported contralateral muscle mass and function assessment observations independently, fewer studies have examined the *relationship* between contralateral and ipsilateral lower extremity muscle mass (and muscle mass asymmetries) and (a) muscle-specific strength and (b) force production. Examining these relationships may help identify athletes at risk for primary or secondary ACL injury, in addition to aiding clinicians in RTS decisions following ACL rehabilitation. In fact, given the high incidence of primary and secondary ACL injury, with high secondary ACL injury risk in either the ipsilateral or contralateral leg, exclusive contralateral *strength* asymmetry assessments may not be adequate to prevent ACL injury or to ensure athletes' readiness to RTS following reconstruction (Paterno et al., 2018; Wellsandt et al., 2017). Thus, examining the relationships between muscle mass and muscle-specific strength and force production is necessary to determine relative muscle functionality and perhaps gain a greater understanding of underlying primary and secondary ACL injury mechanisms.

Association of Lean Mass & Force Production in Healthy & ACLR Athletes

Examining lean muscle mass's relationship with muscle-specific strength and force production in healthy athletes (i.e., a population potentially at risk for primary ACL injury) and ACLR athletes at risk for secondary ACL injury is important. Specifically, conducting investigations to assess how contralateral and ipsilateral lean mass, and lean mass asymmetries, contribute to athletes' muscle function and performance outcomes is paramount. To date, most studies have primarily employed muscle strength testing within the sport performance and rehabilitation settings, while fewer studies (Akagi et al., 2014; Denadai et al., 2016; Bell et al., 2014; Jordan et al., 2015; Konishi et al., 2007, 2011) have reported concurrently assessing lean mass and strength and the relationship between these measures. Notably, in a recent systematic review, Bishop and colleagues (2018) highlighted the scarcity of current literature focused on assessing: (a) the relationship between lean mass and strength/force production in both healthy and ACLR athletes; and (b) the effects that contralateral lean mass asymmetries have upon healthy and ACLR athletes' performance outcomes. Examining these relationships, not only contralaterally but also ipsilaterally, may better elucidate muscle mass's contribution to functional asymmetries reported previously (Konishi et al., 2011). This assessment may allow for determination of athletes' degree of relative muscle functionality translating to sport performance.

Therefore, the relationships between (a) muscle mass measured using CT or MRI and muscle-specific strength and (b) lean mass measured using DXA in the frontal view and jump mechanography-measured force production reported thus far in healthy and ACLR athletes are reviewed below.

Isokinetic/Isometric Dynamometry & Muscle Mass Assessments

To date, when examining lower extremity muscle, researchers have commonly measured quadriceps and hamstring muscle CSA and MV using CT and MRI, particularly in relation to isokinetic and isometric knee extensor and flexor peak torque, respectively (Akagi et al., 2014; Denadai et al., 2016; Konishi et al., 2011, 2012; Masuda et al., 2003). These investigations have been completed in healthy and ACLR athletes and non-athletes and provide insight regarding relative muscle-specific functionality. While earlier studies reported a direct relationship between muscle CSA and peak torque (Schantz et al., 1983), in addition to reporting muscle size as a major muscle strength determinant (Fukunaga et al., 2001), more recent studies have observed mixed correlations between these variables.

Healthy Subjects. In a sample of healthy collegiate soccer players, Masuda et al. (2003) reported significant moderate relationships between quadriceps and hamstring CSAs (examined separately) and knee extensor (r=0.54-0.59; p<0.05) and knee flexor (r=0.57-0.64; p<0.05) isokinetic peak torque, respectively (at 90 and 120°/sec). However, studies (Akagi et al., 2012; Akagi et al., 2014; Denadai et al., 2016) that have investigated the relationship between the reciprocal (i.e., hamstring/quadriceps [H/Q]) muscle size ratio and the reciprocal isokinetic/isometric strength ratio in healthy athletes have reported low, non-significant correlations. Briefly, in male soccer players, Akagi et al. (2014) and Denadai et al. (2016) reported low correlations (r = -0.33 to 0.28; p>0.05) between (a) H/Q muscle size (CSA and MV) and (b) H/Q peak torque (isokinetic and isometric). This research suggests examining muscle groups separately in relation to isokinetic/isometric peak torque (e.g., quadriceps muscle mass vs. extensor peak torque) produces higher correlations than when comparing reciprocal muscle size and strength ratios.

ACLR Subjects. When assessing the relationship between lean mass and muscle-specific strength in ACLR subjects, most studies have examined this relationship in physically active non-athletes with prior ACL reconstruction, while few researchers have conducted this investigation in ACLR athletes. In a sample of physically active non-athletes (mean age: 24.7±5.2 yrs.) approximately 14 months following ACL reconstruction, Konishi et al. (2011) reported these ACLR individuals to produce significantly lower isokinetic extensor peak torque (at 60°/sec) per unit of quadriceps MV (measured via MRI) in their involved versus non-involved legs (0.086±0.019 Nm/cm^3 vs. 0.100±0.016 Nm/cm^3; $p<0.05$), and in both legs versus an age-matched control groups' legs (at 60 and 180°/sec; $p<0.01$). These observations corroborated Konishi et al. (2007)'s earlier observations in physically active individuals ≤12 months post-ACL reconstruction. In this study, ACLR individuals produced lower peak torque per unit quadriceps MV at 60 and 180°/sec in their involved versus non-involved legs ($p<0.05$) as well as both legs versus healthy controls' legs ($p<0.01$). Given the preceding findings, these researchers concluded bilateral quadriceps neural inhibition (i.e., AMI) was present after ACL injury, resulting in reduced motor unit recruitment from decreased afferent feedback.

In a more recent investigation, Thomas et al. (2016) examined the contribution of (a) quadriceps muscle CSA atrophy (measured via MRI) and (b) quadriceps muscle activation to quadriceps weakness measured during isometric testing in participants 6 months post-ACL reconstruction (mean age: 20.7±5.2 yrs.). These researchers reported that quadriceps muscle CSA atrophy significantly contributed to quadriceps strength deficits (R^2=0.307; p=0.011) and noted muscle CSA and isometric strength measurements were significantly lower in ACLR participants' involved leg (68.81±17.80 cm^2; 2.03±0.51 Nm/kg) versus their non-involved leg (81.10±21.58 cm^2; 2.89±0.81 Nm/kg; $p<0.001$).

Although muscle activation was not observed to explain the variance in quadriceps strength deficits (*R^2*<0.001)—similar to observations reported by Kuenze et al. (2016)—these researchers noted bilateral quadriceps activation failure of 13% and 15% in the involved and non-involved legs, respectively. These percentages are similar to those reported by Urbach et al. (1999) and above the 5% threshold considered healthy (Stackhouse et al., 2000). Finally, it is noteworthy that Thomas et al. (2016) indicated quadriceps CSA atrophy and activation failure, in combination, explained 38% of the variance in quadriceps strength (R^2=0.38; *p*=0.016). These researchers hypothesized other factors to explain the other 62% variance in strength, including muscle fiber type, muscle architecture (e.g., fiber pennation angle), and knee joint pain—factors not examined in their study.

Despite research assessing the relationship between muscle size/mass and muscle-specific strength in healthy and ACLR individuals, it is notable that no studies to date have examined this relationship among ACLR *adolescent female* athletes. Further, no known study in any population has employed the lateral DXA scanning method (Raymond et al., 2017) to investigate the relationship between upper-leg compartmental lean mass and isokinetic knee extensor/flexor peak torque. Notably, examining lateral view compartmental upper-leg lean mass using DXA would offer two distinct advantages. First, while most studies have utilized CT and MRI to examine quadriceps and hamstring muscle CSA/MV, these methods are not practical in the sport performance or rehabilitation settings due to these methods' high cost, long scan times, CT's high ionizing radiation, and results that may be difficult to analyze. Second, examining the association of compartmental lean mass and muscle-specific strength may offer a more detailed analysis of how specific muscles' functionality contributes to performance outcomes—possibly aiding in training and rehabilitation program development to reduce primary and secondary ACL injury risk.

Jump Mechanography & Muscle Mass Assessments

While most studies have used CT and MRI to examine muscle size/mass, researchers (Bell et al., 2014; Jordan et al., 2015; Stephenson et al., 2015) have more recently employed DXA to measure lower extremity lean mass. Further, these researchers have assessed the association between contralateral lower extremity lean mass and jump mechanography-measured force production in healthy and ACLR athletes to estimate relative muscle functionality. This is particularly important as DXA is considered a *practical gold standard* criterion body composition method within the sport performance setting (Stewart & Sutton, 2012), and jump mechanography offers greater biomechanical specificity to sport performance (Impellizzeri et al., 2007). Briefly, these studies examined the association of lower extremity (e.g., total-leg, upper-leg) lean mass (measured via DXA in the standard frontal view) and jump height, force, impulse, and power produced during the CMJ and SJ. Additionally, these researchers aimed to determine how lower extremity lean mass *asymmetries* influenced the preceding jump mechanography-measured variables in healthy and ACLR athletes and non-athletes.

Healthy Subjects. In healthy, physically active non-athletes, Stephenson et al. (2015) reported a positive relationship between total-body and total-leg lean mass with CMJ jump height (r=0.73; p<0.001) and peak power (r=0.74; p<0.001). Among healthy NCAA Division I collegiate athletes, Bell et al. (2014) were among the first researchers to examine the relationship between athletes' lean mass *asymmetries*—calculated via the limb symmetry index (LSI = [(Right Limb – Left Limb) / (0.5(Right Limb + Left Limb))] x 100)—and (a) jump height and (b) force production asymmetries during a CMJ. Age- and sex-adjusted analyses revealed upper- and lower-leg lean mass asymmetries only partially explained asymmetries in CMJ peak force (R^2=0.20; p<0.001) and peak power (R^2=0.25; p<0.001) (Bell et al., 2014). These researchers also reported contralateral upper-leg lean mass asymmetries >10% significantly contributed to jump height reductions (-9 cm; effect size = d >0.8). Therefore, these studies indicated that not only does leg lean mass directly contribute to force production, contralateral leg lean mass *asymmetries* contribute to force asymmetries and reduced jump height in healthy individuals.

ACLR Subjects. Due to the more recent use of jump mechanography, only a paucity of literature has reported the association between lower extremity lean mass and jump mechanography-measured force production asymmetries in ACLR athletes. Jordan and colleagues (2015) have conducted the most relevant research. Specifically, in a case-control study, Jordan et al. (2015) investigated contralateral DXA-assessed upper-leg lean mass and CMJ and SJ phase-specific impulse asymmetry differences between healthy (i.e., control) and ACLR elite alpine skiers, with ACLR athletes being 2 years post-reconstruction. This study reported significant upper-leg lean mass asymmetry index (AI) differences (calculated as: AI = [(Left limb – Right limb) / (Maximum of left and right)] x 100) between ACLR and control groups (4.3% vs. -2.2%; p<0.001). Additionally, significant impulse AI differences were observed between the ACLR and control groups during the CMJ's concentric phase (6.5% vs. 0.5%; p<0.05) and the second half of the SJ's concentric phase (8.8% vs. -1.0%; $p<0.05$)—movement phases which primarily use the knee extensors to generate force. Finally, using linear regression analysis, Jordan et al. (2015) reported moderate correlations between upper-leg lean mass AI and impulse AI ($r=0.57$-0.66; $p<0.01$) in the CMJ's concentric phase and the SJ's second phase. These observations demonstrate a direct relationship between asymmetries in DXA-measured frontal view leg lean mass and jump outcomes.

Taken together, observations of the relationship between contralateral lean muscle mass asymmetries and strength and force production deficits and asymmetries—particularly quadriceps asymmetries—have three notable implications as it pertains to ACL injuries. First, these observations suggest muscle mass and strength deficits and subsequent asymmetries may hinder performance and increase primary and secondary ACL injury risk. Second, the investigations reviewed indicated that a prior ACL injury may prevent adequate strength gains (via neuromuscular mechanisms like AMI) during rehabilitation—allowing strength asymmetries to persist and increasing secondary ACL injury risk if proper rehabilitation is not undertaken. Finally, these studies suggested that dynamic assessment methods like isokinetic dynamometry and jump mechanography are useful to detect muscle function imbalances possibly increasing secondary ACL injury risk.

Summary

While researchers have examined athletes' lower extremity lean muscle mass, muscle-specific strength, and force production independently—and asymmetries in these measures—fewer studies have examined the *relationship* between lower extremity lean mass and the preceding functional strength measures. These studies have primarily reported assessing the following relationships: (a) muscle CSA/MV versus isokinetic/isometric peak torque; or (b) frontal view DXA-measured lean mass versus jump mechanography-derived force production. Further, most of these studies examined the preceding relationships in healthy athletes and physically active non-athletes to estimate muscle functionality. Fewer researchers, however, have evaluated these associations in ACLR athletes, and no known studies have reported examining these relationships in ACLR *adolescent female* athletes—a population with the highest ACL injury risk (Ardern et al., 2016). Finally, although contralateral lean mass and muscle strength/force production asymmetries are important to examine in healthy and ACLR athletes, *ipsilateral* upper-leg compartmental lean mass evaluation is likely to provide greater insight into muscle-specific functionality and ACL injury risk.

Our laboratory developed and demonstrated the accuracy of a lateral DXA scanning method to examine upper-leg compartmental (i.e., ipsilateral) lean mass to address the preceding limitations (Raymond et al., 2017). However, validation of this assessment has only been conducted on one DXA scanner model. Therefore, evaluating this novel scanning method's accuracy on a DXA scanner made by a different manufacturer is important and may allow for this method's more widespread use in the sport performance and rehabilitation settings. Additionally, no studies have examined lateral view DXA-measured upper-leg compartmental lean mass in relation to isokinetic peak torque and jump mechanography-measured force production in healthy or ACLR athletes. This assessment is warranted to examine how lean mass influences muscle function, and how this relationship changes as a result of prior ACL injury. Thus, conducting studies which fill these literature gaps is important.

CHAPTER 3. ASSESSING AGREEMENT OF LATERAL LEG MUSCLE AND BONE COMPOSITION USING DUAL X-RAY ABSORPTIOMETRY

Assessing Agreement of Lateral Leg Muscle and Bone Composition Using Dual X-ray Absorptiometry

Authors: Christiana J. Raymond-Pope, M.S.[1], Tyler A. Bosch, Ph.D.[2], Donald R. Dengel, Ph.D.[1,3]

[1]Laboratory of Integrative Human Physiology, School of Kinesiology, University of Minnesota, Minneapolis, MN 55455
[2]College of Education and Human Development, University of Minnesota, Minneapolis, MN 55455
[3]Department of Pediatrics, University of Minnesota Medical School, Minneapolis, MN 55455

Short Title: Assessing Lateral Leg Composition Using DXA
Key Words: DXA, lean mass, fat mass, bone mineral content, subject positioning

Publication Reference: Raymond-Pope, CJ, Bosch, TA, Dengel, DR. Assessing Agreement of Lateral Leg Muscle and Bone Composition Using Dual X-ray Absorptiometry. Submitted to *Journal of Clinical Densitometry* 2019.

Disclosures: The authors declare there is no competing or conflict of interest associated with this research study. Christiana J. Raymond-Pope prepared the first draft of the manuscript without any associated honorarium, grant, or other form of payment to produce the manuscript.

Summary

Purpose: Recently, a lateral-view dual X-ray absorptiometry (DXA) scanning method for measuring leg total (TM), lean (LM), and fat (FM) masses demonstrated accuracy vs. the standard whole-body frontal DXA scanning view on the GE Lunar iDXA. The current study examined the lateral scanning method's agreement using a Hologic Horizon A DXA scanner. **Methods:** Thirty healthy college-age participants (16 female; $\bar{X}_{age}$= 21.5±1.7 yrs.) received three DXA scans (1 whole-body, 2 lateral leg scans) to quantify leg composition in the frontal and lateral plane. To mark regions of interest (ROIs) for post-scan analysis, metallic markers were placed at 60% of the length above and below each leg's lateral epicondyle. Using lateral subject positioning, leg composition was measured with participants lying on their right/left sides. Paired t-tests examined the lateral DXA scanning method's agreement when quantifying TM, LM, FM, bone mineral content (BMC), and bone mineral density (BMD) compared to measurements of equal area in the whole-body frontal scanning view. **Results:** Comparisons of frontal and lateral view DXA scan measurements for right leg TM (7.12±0.91kg vs. 6.39±0.85kg), FM (1.70±0.44kg vs. 1.36±0.33kg), LM (5.14±1.05kg vs. 4.77±0.92kg), BMC (0.28±0.06kg vs. 0.23±0.05kg), and BMD (1.39±0.14g/cm^2 vs. 1.36±0.15g/cm^2), respectively, were significantly different (p<0.001 to 0.028). Similarly, comparisons of frontal and lateral left leg TM (7.12±0.97kg vs. 6.38±0.92kg), FM (1.70±0.44kg vs. 1.39±0.36kg), LM (5.15±1.12kg vs. 4.76±0.97kg), BMC (0.28±0.06kg vs. 0.24±0.06kg), and BMD (1.39±0.15g/cm^2 vs. 1.36±0.17g/cm^2) respectively, were significantly different (p<0.001 to 0.046). **Conclusion:** Unlike a previous study in which agreement of lateral vs. frontal leg composition measurements of

equal area was reported utilizing the GE Lunar iDXA, agreement was not observed using the Hologic Horizon A DXA scanner. Therefore, lateral view assessment may not be reliably performed on DXA scanner models produced by different manufacturers.

Introduction

Dual X-ray absorptiometry (DXA) is currently considered the *gold standard* for accurately and reliably measuring total and regional (e.g., arms, legs) body composition and bone mineral density (BMD) (Bilsborough et al., 2014; Burkhart et al., 2009; Haarbo et al., 1991; Lee & Gallagher, 2008; Mazess et al., 1990; Nana et al., 2014; Stewart et al., 2001). In clinical settings, DXA is commonly used to assess: osteoporosis risk or presence (Lewiecki, 2005); visceral adipose tissue (Bosch et al., 2015; Kaul et al., 2012) and lean mass loss due to disease conditions (e.g., cancer, stroke, sarcopenia) (Glickman et al., 2004; Hairi et al., 2010; Lewiecki, 2005; Nana et al., 2014). More recently in the sport performance setting, DXA has been used to: examine longitudinal body composition changes due to training and nutritional interventions (Ackland et al., 2012); examine athletes' lean and fat mass distribution (Bosch et al., 2014, 2018); and assess contralateral (i.e., opposite side) lower extremity lean mass imbalances that may hinder athletes' performance (Bell et al., 2014; Jordan et al., 2015; Krzykala & Leszczynski, 2015).

Currently, three major manufacturers produce DXA scanners, including GE Healthcare Lunar Inc. (Madison, WI, USA), Hologic Inc. (Marlborough, MA, USA), and Norland Inc. (Swissray, Fort Atkinson, WI, USA), with the two primary manufacturers being GE and Hologic (Bazzocchi et al., 2016). While advancements in DXA technology have been made across these manufacturers, with the most recent models being the GE Lunar iDXA, Hologic Horizon, and Norland Elite systems, these systems differ in their analysis software and scanning geometry—factors which influence scan time, radiation dose, and accuracy (Slater, O'Connor & Pelly, 2013). Specifically, while Norland continues to produce pencil-beam scanners, the transition from pencil-beam to fan-beam (Hologic Horizon A) and to narrow fan-beam (GE Lunar iDXA) technology has allowed for a decreased scan time while improving image resolution and quality (Bazzocchi et al, 2016). Further, the most recent DXA software has demonstrated accuracy and reliability in the automatic and manual creation of regions of interest (ROIs) when assessing body composition in specific body regions (Bazzocchi et al., 2016; Burkhart et al., 2009). For example, previous studies have examined contralateral lower extremity body composition asymmetries via manual ROIs in the standard frontal DXA scan view (Bell et al., 2014; Hart et al., 2015; Jordan et al., 2015; Jorgensen & Jacobsen, 2001; Krzykala & Leszczynski, 2015). However, to date, only one known study has reported the accuracy of assessing leg composition in the lateral view compared to the standard total-body frontal view using the GE Lunar iDXA (Raymond et al., 2017). Additionally, the lateral DXA scanning view demonstrated reliability when segmenting the upper-leg into anterior (quadriceps) and posterior (hamstrings) compartments to quantify composition in these regions (Raymond et al., 2017). The lateral DXA scanning method may therefore allow for a more in-depth analysis of contralateral and ipsilateral upper-leg compartmental comparisons and provide greater insight into compositional asymmetries resulting from disease conditions in clinical populations or training in athletic populations.

As the lateral DXA scanning method has only demonstrated accuracy on the GE Lunar iDXA (Raymond et al., 2017), the current study's aim was to examine the agreement of the lateral scanning method when using the Hologic Horizon A DXA scanner. This investigation is important as previous studies have reported differences in body composition estimates across different DXA scanner models produced by GE Healthcare Lunar, Hologic, and Norland (Genton et al., 2005; Hull et al., 2009; Tothill et al., 1994a; Tothill et al., 1994b; Tothill et al., 2001; Toombs et al., 2012). Further, as the previous study (Raymond et al., 2017) did not assess the accuracy of measuring lateral view bone mineral content (BMC) or bone mineral density (BMD) in comparison to the standard whole-body frontal view, we therefore aimed to assess these variables' agreement between scan views. We hypothesized that total, fat, and lean masses, BMC, and BMD measured in the lateral scanning view would be similar to measurements of equal area obtained in the standard whole-body frontal scanning view. If demonstrated accurate and reliable, this DXA scanner would offer researchers, health professionals, and sports practitioners an additional scanner for use in making upper-leg compartmental (i.e., anterior/posterior) composition assessments and allow for longitudinal monitoring of patients' muscle and bone composition changes in response to individualized training and rehabilitative programs.

Methods

Study Participants

Thirty (14 male/16 female) college-age participants (mean age 21.5±1.7 years) were recruited from the University of Minnesota-Twin Cities campus. Participants were healthy, self-reported physical activity at least three days per week for at least three months prior to study participation and had a body mass index (BMI) >18 kg/m^2. The study protocol was approved by the University of Minnesota Institutional Review Board, and written informed consent was obtained from all participants prior to data collection.

Scan Procedures

All testing was performed on the University of Minnesota-Twin Cities campus using a Hologic Horizon A DXA scanner (Hologic Inc., Marlborough, MA, USA). Each participant's height and weight were measured using an electronic scale and wall-mounted stadiometer (Model S100; Ayrton Corp., Prior Lake, MN, USA). Body mass index (BMI) was calculated as the body weight in kilograms divided by height in meters squared. All participants wore minimal, light clothing free of metallic material for DXA scans, with females screened for pregnancy prior to undergoing DXA scans. Prior to being positioned for the DXA scans, each participant's standing right and left leg lengths were measured using a tape measure. Metallic markers were then placed at 60% of the length above and below each leg's lateral epicondyle (i.e., from the lateral epicondyle to the greater trochanter and from the lateral epicondyle to the lateral malleolus, respectively) for post-scan analysis ROI boundary placement (Figure 1). These lengths and boundaries were chosen according to previously described procedures (Raymond et al., 2017), thereby ensuring the largest assessment area was included without contralateral leg overlap in the lateral scan view. Notably, as the Hologic Horizon A DXA scanner's software does not allow for ruler measurement in the post-scan's "sub-region analysis" mode, marking these boundaries on the right and left legs' frontal and lateral aspects prior to scans was necessary for manual ROI creation.

Following metallic marker placement, all participants received three DXA scans (1 whole-body, 2 lateral leg) to quantify and compare leg composition in the frontal and lateral views. Total-body composition was measured using standard procedures in the supine position, and scans were analyzed using Hologic Apex software (Apex Version 5.6.0.4, Hologic Inc., Marlborough, MA, USA). Following the whole-body scan, participants underwent two leg scans (right and left), using the whole-body scan mode, to quantify total, fat, and lean masses, BMC, and BMD in the lateral view. Table length was measured and entered into the computer to ensure leg scans were completed when the DXA's arm reached the shoulder, thereby excluding the head. Participants were repositioned for these segmented lateral scans as described previously by Raymond et al. (2017).

Segmentation Procedures

Upon DXA scan completion, a two-dimensional image was automatically produced for post-scan analysis. To examine the agreement of the lateral scanning method's measurements in comparison to the whole-body frontal scanning method's measurements, ROIs of equal area were created on the lateral and frontal scans, respectively, using the boundaries outlined by the metallic markers. Using the Hologic Apex software, the ruler function in the whole-body analysis mode was used to first ensure equal lengths and areas were represented by the metallic marker boundaries in the frontal and lateral views. Following ruler measurements, manual ROIs were created in the sub-region analysis mode. Specifically, in both the frontal and lateral views, the proximal and distal ROI borders were drawn at the level of the metallic markers placed at 60% of the length from (a) the lateral epicondyle to the greater trochanter and (b) the lateral epicondyle to the lateral malleolus, respectively. Lateral and medial ROI box borders were placed outside each leg's area, ensuring inclusion of the entire leg within the boundaries described. Following ROI border placement, total mass, fat mass, lean mass + BMC, BMC, and BMD were recorded. As the

Hologic Apex software does not directly provide lean mass measurements, the BMC measurements were subtracted from the [lean mass + BMC] measurements, thereby giving lean mass values.

Statistical Analyses

To examine the agreement of the lateral DXA scanning method using the Hologic Horizon A DXA scanner, paired t-tests were used to compare compositional measurements obtained from the lateral DXA scan view to the whole-body frontal scan view. All compositional comparisons were calculated as [frontal mass – lateral mass]. All data were analyzed using statistical analysis software (RStudio, Version 1.0.143; Boston, MA), with α set at 0.05 for paired t-tests.

Results

Table 1 presents participant descriptive characteristics. Right and left leg total mass, fat mass, lean mass, BMC, and BMD measurements for lateral and whole-body frontal scans are displayed in Table 2. Additionally, Table 2 presents mean differences ± SD and associated 95% confidence intervals between the lateral and whole-body frontal DXA scans for right and left leg total mass, fat mass, lean mass, BMC, and BMD measurements. Notably, leg composition comparisons between the frontal and lateral scan views, including total, fat, and lean masses, BMC, and BMD were all significantly different (p<0.001 to 0.046). Males and females are presented together in Table 2 as significant differences were observed for all composition variables in males and females separately (p-value range of 0.005 to <0.001), except for males' right (p=0.72) and left (p=0.94) leg BMD (mean differences = 0.0075 g/cm^2 and 0.0014 g/cm^2, respectively). Figure 2 displays differences for each participant's left and right leg lean (A-B) and total (C-D) masses, and Figure 3 displays differences for each participants' left (A) and right (B) leg BMD, with the mean difference for each figure's panel shown as a solid black vertical line.

Discussion

To our knowledge, only one study (Raymond et al., 2017) has assessed the accuracy of leg composition measurements obtained in the lateral scan view in comparison to standard whole-body frontal scan view measurements, with this study using a GE Lunar iDXA. Utilizing the same scan procedures, the present study evaluated the agreement of lateral scan view leg composition measurements compared to standard frontal view measurements using the Hologic Horizon A DXA scanner. The current study's observations revealed significant differences across all leg composition measurements—including total, fat, and lean masses, BMC, and BMD—between the lateral and frontal DXA scanning views using this manufacturer's scanner. In detail, the lateral view underestimated all measurement variables.

While previous studies (Burkhart et al., 2009; Hart et al., 2015; Kerr et al., 2016) utilizing DXA have reported the accuracy of total and regional body composition measured using frontal view supine subject positioning, fewer studies (Lambrinoudaki et al., 1998; Lohman et al., 2009) have assessed the accuracy of various subject positioning protocols in a different scan view compared to standard frontal supine subject positioning. In fact, most of these prior studies investigated prone vs. supine positioning. For example, a seminal study (Lambrinoudaki et al., 1998) utilizing the Hologic QDR 2000 fan-beam DXA scanner compared prone and supine body composition measurements in 30 healthy participants (age range = 16-69 yrs). Lambrinoudaki et al. (1998) reported prone positioning to significantly underestimate total BMC, total fat mass, and trunk lean mass, with total lean mass overestimation (all $p<0.001$). These observations were similar to a study conducted by Lohman and colleagues (2009) in 30 males (age range = 22-61 yrs)—using a GE Lunar Prodigy narrow fan-beam DXA scanner—in which the reproducibility of total and regional body composition measurements was examined in three consecutive positions: supine, prone, and supine. When performing correlations between the first supine scan vs. the (a) prone and (b) second supine scans, Lohman et al. (2009) reported slightly lower correlations between repeated values in supine-prone (r=0.70 to 0.90) than in supine-supine (r=0.75 to 0.95) measurements. Notably, these researchers concluded that differences in subject positioning affect DXA body composition measurements due to slight changes in tissue depth and fat distribution between positions. Specifically, as DXA provides a 2-dimensional image of a 3-dimensional object, small geometric projective errors may result due to depth changes of particular anatomical regions in relation to the scanner (Lambrinoudaki et al., 1998; Lohman et al., 2009).

Assessing the accuracy of lateral DXA scanning measurements is also important. Briefly, lateral DXA scanning position assessment would allow for upper-leg compartmental (anterior/posterior) composition quantification, perhaps allowing for a more in-depth analysis of contralateral and ipsilateral upper-leg compartmental comparisons. These may provide greater insight into compositional asymmetries affecting the health of clinical population and athletes' sport performance. In the only known study to examine the accuracy of the lateral DXA scanning view, Raymond et al. (2017) observed no significant measurement differences between lateral and frontal DXA scanning views for total, fat, and lean mass measurements (*p*-value range: 0.15-0.91) utilizing the GE Lunar iDXA scanner (Raymond et al., 2017). The preceding observations contrast with the current study's observations wherein significant differences were seen for all measurements between the lateral and frontal scan views using the Hologic Horizon A DXA scanner. Further, the current study's observations add to the literature by providing information regarding lateral view BMC and BMD measurements in comparison to frontal view measurements using the Hologic Horizon A. These measurement differences between scan views followed the same trend as those observed for total, fat, and lean masses.

The differences between the observations reported by Raymond et al. (2017) and those of the current study may be due to a few factors. First, literature has noted that the inability to draw curved lines in the manual creation of ROIs during the post-scan analysis may contribute to errors, as researchers may be including more or less mass within the ROI than desired (Burkhart et al., 2009). Second, Burkhart et al. (2009) reported subject movement as a major source of error given movement's effect upon DXA image resolution and quality. Finally, as mentioned, researchers have hypothesized that differences between various subject positioning views (e.g., supine vs. prone) may result in differences in tissue depth and the alteration of scan attenuation ratios (Lambrinoudaki et al., 1998; Lohman et al., 2009). However, in the current study, a single trained technician conducted all DXA scans—ensuring no participant movement during the scans—and analyzed all scans utilizing manual ROIs according to procedures described by Raymond et al. (2017).

Therefore, this study's systematic manual ROI creation ensured ROIs of equal area were drawn in the lateral and frontal DXA scanning views.

Perhaps the greatest contributor to the incongruent observations made in the present study compared to previous observations (Raymond et al., 2017) is the difference in DXA scanner model and manufacturer used in these studies. Notably, previous research has indicated DXA image resolution and quality to vary between DXA scanner models and manufacturers (e.g., GE, Hologic, Norland) (Genton et al., 2005; Soriano et al., 2004; Toombs et al., 2012; Tothill et al., 1994a; Tothill et al., 1994b; Tothill et al., 2001). This is largely due to differences in the manufacturers' proprietary analysis software, in which different algorithms are used to calculate fat, lean, and bone masses (Toombs et al., 2012; Van Loan et al., 1995), in addition to differences in hardware and scanner geometry (i.e., fan-beam vs. narrow fan-beam) (Slater et al., 2013). In fact, these hardware and software differences have been reported to contribute to differences in total and regional body composition estimates between DXA scanner models produced by different manufacturers (Genton et al., 2005; Soriano et al., 2004; Toombs et al., 2012; Tothill et al., 2001) and different DXA scanner models produced by a single manufacturer (e.g., GE Lunar Prodigy vs. GE Lunar iDXA; Hull et al., 2009). When this reasoning is applied to the current study's observations, it is noteworthy that the Hologic Apex software allows only for manipulation of ROI box size and placement within the sub-region post-scan analysis mode but does not allow for separate ROI lines to be drawn—a feature available in the GE enCore™ software used by Raymond et al. (2017). Therefore, the feasibility of performing the lateral DXA scanning method on DXA scanners produced by different manufacturers appears to be limited due to manufacturers' hardware and software differences.

Major strengths of the current study include the study population's wide body composition range (BMI range: 18.8-27.5 kg/m^2)—similar to the study population (BMI range: 19.0-32.0 kg/m^2) assessed by Raymond et al. (2017)—and inclusion of males and females. Second, all leg measurements were made prior to conducting lateral and frontal DXA scans, and these measurements were marked by metallic markers (Figure 1)—ensuring all measurement leg lengths and ROI areas were equal between scans. These measurement lengths and areas in the frontal and lateral views were verified using the Hologic Apex software's ruler function.

Conclusion

In conclusion, while lateral subject positioning has previously demonstrated accuracy in quantifying lower extremity body composition in comparison to measurements of equal area in the standard whole-body frontal view using a GE Lunar iDXA (Raymond et al., 2017), the current study did not observe agreement between the two views using the Hologic Horizon A DXA scanner. These observations indicate caution should be used when examining leg composition in the lateral view using a Hologic Horizon A DXA scanner—perhaps limiting the reliability of performing this measurement method on multiple DXA scanner models.

Table Legends

Table 1. Study Participant Characteristics

Table 2. Mean Measurement Values and Paired t-test Results Between Frontal and Lateral DXA Scan Views

Tables

Table 1. Study Participant Characteristics

	Male	**Female**	**Total**
n	14	16	30
Age (yr)	21.6±2.0	21.3±1.4	21.4±1.7
Body weight (kg)	77.4±8.9	61.0±4.6	67.6±11.5
Height (m)	1.78±0.08	1.64±0.1	1.71±0.1
BMI (kg/m^2)	24.3±2.4	21.9±1.9	23.1±2.5
Percent Body Fat (%)	16.9±2.5	27.6±2.5	22.6±5.9
Total Fat Mass (kg)	13.0±1.7	16.6±1.9	14.9±2.6
Total Fat-Free Mass (kg)	64.4±10.3	43.5±3.8	53.3±12.9
Total Lean Mass (g)	61.5±9.5	41.3±3.6	50.7±12.4

Abbreviations: BMI, body mass index

Age, body weight, height, BMI, percent body fat, total fat mass, total fat-free mass, and total lean mass are presented as mean ± SD.

Table 2. Mean Measurement Values and Paired t-test Results Between the Frontal and Lateral DXA Scan Views

Side	**Variable**	**Frontal View**	**Lateral View**	**Mean Difference ± SD**	**95% Confidence Interval**
Right	Total Mass (kg)	7.12±0.91	6.39±0.85	0.73±0.23	0.64, 0.82
	Fat Mass (kg)	1.70±0.44	1.36±0.33	0.34±0.15	0.28, 0.40
	Lean Mass (kg)	5.14±1.05	4.77±0.92	0.38±0.23	0.29, 0.46
	BMC (kg)	0.28±0.06	0.23±0.05	0.05±0.05	0.03, 0.07
	BMD (g/cm^2)	1.39±0.14	1.36±0.15	0.03±0.07	0.00, 0.04
Left	Total Mass (kg)	7.12±0.97	6.38±0.92	0.74±0.25	0.65, 0.84
	Fat Mass (kg)	1.70±0.44	1.39±0.36	0.31±0.17	0.25, 0.37
	Lean Mass (kg)	5.15±1.12	4.76±0.97	0.39±0.24	0.30, 0.48
	BMC (kg)	0.28±0.06	0.24±0.06	0.04±0.01	0.04, 0.05
	BMD (g/cm^2)	1.39±0.15	1.36±0.17	0.02±0.06	0.00, 0.05

P-values and 95% Confidence Intervals were calculated using paired t-tests of the mean difference ± SD of each measure. Mean differences were calculated as [Frontal Scan – Lateral Scan Measurements]. Abbreviations: BMC, bone mineral content, BMD, bone mineral density.

Figures

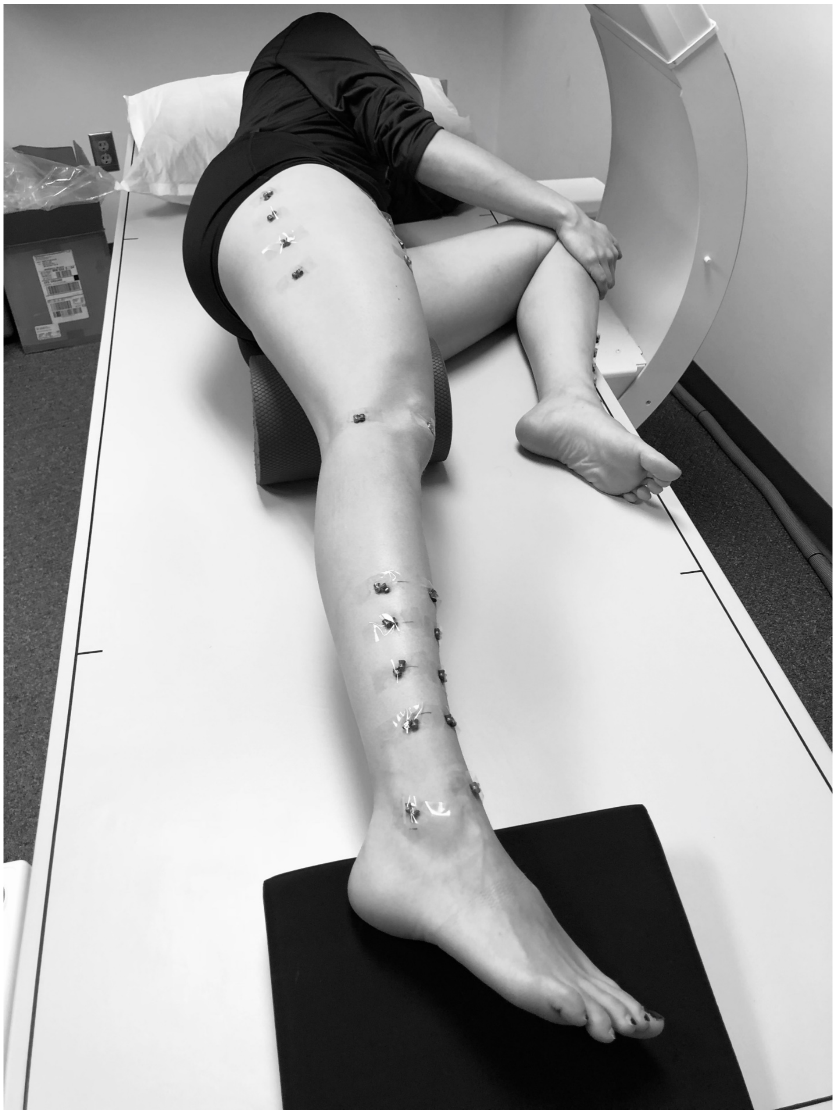

Figure 1. Lateral Subject Positioning and Metallic Marker Placement

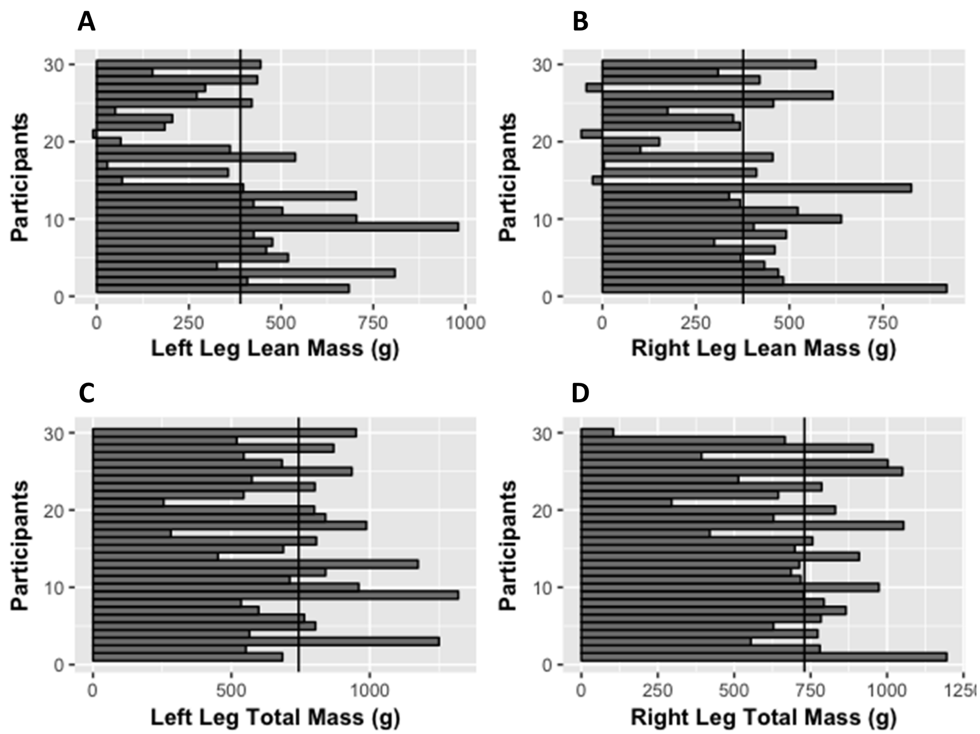

Figure 2. Individual Participants' Mean Differences for Left and Right Leg (A-B) Lean Mass and (C-D) Total Mass

Note: Solid black vertical line on each panel represents the mean of the mean difference for each respective leg measurement.

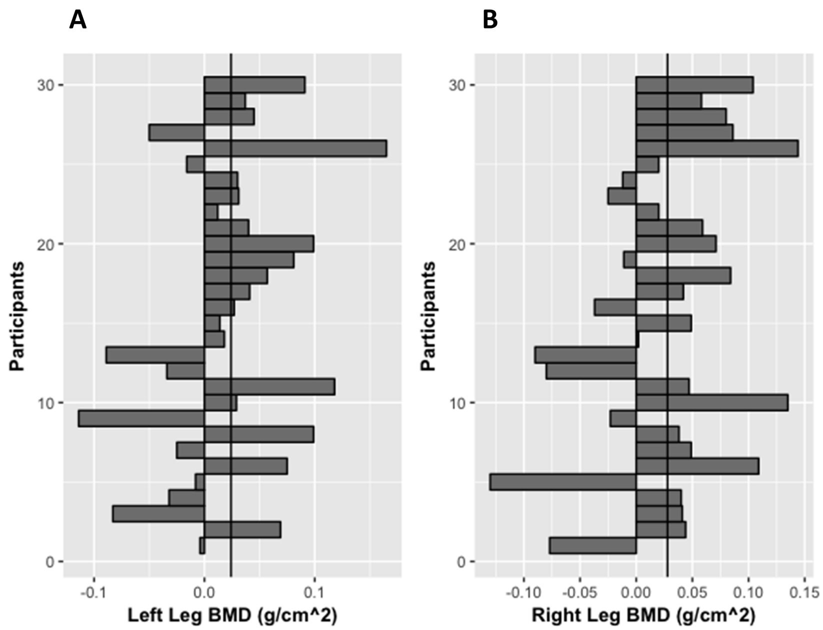

Figure 3. Individual Participants' Mean Differences for Left (A) and Right (B) Leg Bone Mineral Density (BMD)

Note: Solid black vertical line on each panel represents the mean of the mean difference for each respective leg measurement.

CHAPTER 4. ASSOCIATION OF COMPARTMENTAL LEG LEAN MASS MEASURED BY DUAL X-RAY ABSORPTIOMETRY WITH FORCE PRODUCTION

Association of Compartmental Leg Lean Mass Measured by Dual X-Ray Absorptiometry with Force Production

Christiana J. Raymond-Pope, M.S.[a], John S. Fitzgerald, Ph.D.[d], Donald R. Dengel, Ph.D.[a,b] , Tyler A. Bosch, Ph.D.[c]

[a]Laboratory of Integrative Human Physiology, School of Kinesiology, University of Minnesota, Minneapolis, MN 55455
[b]Department of Pediatrics, University of Minnesota Medical School, Minneapolis, MN 55455
[c]College of Education and Human Development, University of Minnesota, Minneapolis, MN 55455
[d]Department of Education, Health, and Behavior Studies, University of North Dakota, Grand Forks, ND 58202

Short Title: Association of Compartmental Lean Mass with Force
Key Words: lean soft tissue, isokinetic dynamometry, jump mechanography, sports performance

Publication Reference: Raymond-Pope, CJ, Dengel, DR, Fitzgerald, JS, & Bosch, TA. (2018). Association of compartmental leg lean mass measured by dual X-ray absorptiometry with force production. *Journal of Strength and Conditioning Research*. doi:10.1519/JSC.0000000000002688.

Disclosures: The authors declare there is no competing or conflict of interest associated with this research study. Christiana J. Raymond-Pope prepared the first draft of the manuscript without any associated honorarium, grant, or other form of payment to produce the manuscript.

Funding Source: This study was supported by Grant Number I UL 1RR033l83 from the National Center for Research Resources (NCRR) of the National Institutes of Health (NIH) to the University of Minnesota Clinical and Translational Science Institute (CTSI).

Summary

Background: We recently reported a novel method for measuring upper leg anterior/posterior compartmental composition. **Objective:** To determine the association of this method with measures of muscle specific and explosive strength and to compare this method to traditional dual energy X-ray absorptiometry (DXA) measurements of total and upper leg masses. We hypothesize this method will be related to muscle specific strength measured by isokinetic dynamometry and explosive strength measured by jump mechanography. **Methods:** Nineteen NCAA Division I college athletes (10 female; age=20.4±1.4 years; height=1.8±0.1 m; weight=73.8±17.0 kg) underwent three DXA scans (1 total-body, 2 lateral) and knee extension/flexion strength assessment using isokinetic dynamometry at three velocities (60, 120, 180°•s^{-1}). A subset of 10 participants also completed a squat jump on a force platform on a different day. Pearson correlations compared three separate lean soft tissue mass (LSTM) regions of interest (total-leg, upper leg, compartmental leg) with (a) isokinetic peak torque and (b) squat jump height, peak force, and peak and average rate of force development. **Results:** Compartmental leg LSTM demonstrated similar correlations (r=0.437-0.835) with peak torque in comparison with total-leg (r=0.463-0.803) and upper leg (r=0.449-0.795) LSTM. Summed right and left total-leg (r=0.830-0.940), total upper leg (r=0.824-0.953), and anterior (r=0.582-0.798) and posterior (r=0.750-0.951) compartmental leg LSTM demonstrated moderate-to-strong correlations with all squat jump variables, particularly jump height (p<0.05). The lateral segmentation DXA scanning method demonstrated feasibility in assessing compartmental

leg LSTM in relation with isokinetic and squat jump measurements—important outcomes when examining an athlete's response to training and rehabilitation.

Introduction

Body composition, muscle specific strength, and explosive strength (time-restricted force production during a ballistic task) are common assessments in sports performance. Often, these assessments are used as benchmarks for training to optimize performance, assess return to play, or examine injury risk (Ackland et al., 2012; Bloms et al., 2016). Specifically, coaches, physical therapists, and sports medicine professionals utilize isokinetic dynamometry to assess muscle specific strength (often following injury) and employ jump mechanography testing—using the validated (Markovic et al., 2004) countermovement and squat jump techniques—to assess dynamic lower body force production and estimate muscle function (Impellizzeri et al., 2007; Iossifidou et al., 2005). However, not only is the assessment of athletes' absolute strength and force production important for monitoring changes in response to training and rehabilitation, but the examination of these variables in relation to lean muscle mass is necessary in determining relative muscle functionality (Bell et al., 2014; Jordan et al., 2015).

Previous studies have examined muscle size (i.e., volume, cross-sectional area) in relation to force production to assess muscle functionality (Akagi et al., 2014; Denadai et al., 2016; Masuda et al., 2003), reporting muscle size as a major determinant of muscle strength (Fukunaga et al., 2001). These studies have examined the correlation between contralateral (opposite side) and ipsilateral (same side; i.e., quadriceps vs. hamstrings) leg muscle mass and strength characteristics, with both low, non-significant (Akagi et al., 2014; Denadai et al., 2016) and significant moderate (Masuda et al., 2003) correlations reported. However, these studies have used expensive methods, such as computed tomography or magnetic resonance imaging to examine muscle mass—methods which do not offer practicality in the sports performance or rehabilitation settings due to their high cost and results that may be difficult to analyze.

More recently, researchers have utilized dual X-ray absorptiometry (DXA)—currently considered the "*gold standard*" for quick and non-invasive total and regional body composition examination (Haarbo et al., 1991; Lee & Gallagher, 2008; Mazess et al., 1990)—to measure contralateral lower extremity (i.e., total-leg, upper leg) lean soft tissue mass in the frontal view. These studies have reported a direct association between lower extremity lean soft tissue and functional analyses, such as jump mechanography measurements, in athletes (Bell et al., 2014; Jordan et al., 2015; Stephenson et al., 2015). To date, however, no studies have assessed ipsilateral lean soft tissue mass using DXA—measured in the lateral view—in relation to functional assessment methods (e.g., isokinetic dynamometry or jump mechanography). We recently demonstrated the accuracy and reliability of a lateral segmentation DXA scanning method (Raymond et al., 2017), which measures upper leg compartmental (anterior/posterior) composition, that would increase the feasibility of performing ipsilateral lean soft tissue mass measurements, particularly in relation with muscle specific and explosive strength.

Therefore, the purpose of this exploratory study was to determine the association of the lateral segmentation method with measures of muscle specific and explosive strength and to compare this method to traditional DXA measurements of total and upper leg masses. More specifically, the present study sought to: (a) examine and compare the relationship of (i) total leg, (ii) upper leg, and (iii) compartmental (anterior/posterior) leg lean soft tissue mass with strength measured using an isokinetic dynamometer; and (b) assess the relationship of the sum of right and left (i) total leg, (ii) total upper leg, and (iii) anterior and posterior (assessed separately) lean soft tissue mass with squat jump measurements on a single force platform. We hypothesized that the lateral segmentation method for measuring anterior/posterior compartmental lean soft tissue mass would be strongly associated with muscle specific strength during an isokinetic task while also demonstrating some relation to explosive strength during a jumping task. If our hypotheses are correct, this novel measurement method would be useful to examine the relationship of athletes' muscle mass and muscle strength characteristics when assessing relative muscle functionality—particularly to examine athletes' response to training programs or rehabilitation programs following a lower extremity injury (e.g., anterior cruciate ligament tears).

Methods

Experimental Approach to the Problem

The current study utilized a cross-sectional design to examine the association of upper leg compartmental lean soft tissue mass measured using the lateral segmentation DXA scanning method with (a) isokinetic peak torque and (b) squat jump height and jump execution variables. Further, the current study aimed to compare the aforementioned associations to associations observed when examining total-leg and total upper leg lean mass with isokinetic peak torque and squat jump variables.

Subjects

Nineteen NCAA Division I college-age athletes (10 female; age=20.4±1.4 years, range = 18 to 23 years; height=1.8±0.1 m; weight=73.8±17.0 kg) participating in track and field (*n*=14) and football (*n*=5) were recruited from the University of Minnesota-Twin Cities campus. Subjects were healthy and had a body mass index (BMI) >18.5 kg/m^2 (23.6±3.8 kg/m^2). The study protocol was approved by the University of Minnesota Institutional Review Board. All subjects were informed of the risks and benefits of the study prior to giving written informed consent to participate in the study.

Procedures

DXA Scans. All scans were performed at the Clinical and Translational Science Institute on the University of Minnesota campus between 8:00 am and 12:00 pm. Each participant's height and weight were measured using an electronic scale and wall-mounted stadiometer (Model S100; Ayrton Corp., Prior Lake, MN). BMI was calculated as the body weight in kilograms divided by height in meters squared. All female participants were screened for a negative pregnancy test prior to undergoing DXA scans, with all participants wearing light clothing free of metallic material during the DXA scans. Following height and weight measurements, total body composition was measured using standard total-body frontal DXA scanning procedures (GE Healthcare Lunar) in the supine position on a GE Lunar iDXA system (iDXA, General Electric Medical Systems, Madison, WI, USA), with post-scan analyses performed using enCore^{TM} software (platform version 16.3, General Electric Medical Systems, Madison, WI, USA). After the total-body scan, participants underwent two DXA leg scans (right and left), using the full-body scan mode, to quantify fat mass and lean soft tissue mass in the lateral view. Notably, the leg scans were considered complete once the scan reached the shoulder, thereby excluding the head. The scanning procedures for this lateral positioning have been described previously (Raymond et al., 2017).

Upon scan completion, a two-dimensional image was automatically produced for post-scan analysis. The post-scan analysis was then segmented to allow for the assessment of lean soft tissue mass within three regions of interest (ROIs): (i) total-leg in the total-body frontal view; (ii) total upper leg in the total-body frontal view; and (iii) anterior and posterior upper leg compartments in the lateral segmentation DXA scanning view. Total-leg lean soft tissue mass for the right and left leg of each participant were obtained from automatically generated ROIs whereas upper leg lean soft tissue mass was assessed using the procedure previously described by Bell et al. (2014), with the proximal border of the ROI bisecting the femoral neck and the distal border bisecting the lateral epicondyle of the knee. Of note, the medial and lateral borders were drawn to include the entire area of the upper leg. Finally, anterior and posterior compartmental upper leg lean soft tissue mass was examined using procedures previously described by Raymond et al. (2017). Briefly, the anterior ROI borders were placed at the lateral epicondyle (distal), 80% of the length between the lateral epicondyle and greater trochanter (proximal), down the shaft of the femur (medial), and outside of the leg area (lateral). The posterior ROI borders were placed similarly—mirroring the borders of the anterior ROI box. All scans were analyzed by the same technician. This method has been shown

(Raymond et al., 2017) to demonstrate high inter- and intra-rater reliability (coefficients of variation < 4.8%).

Isokinetic Dynamometry. Following DXA scans, participants performed standard procedures of unilateral right and left knee flexion and extension on a Biodex System 3 Pro (Biodex Medical Systems, Shirley, NY) isokinetic dynamometer to assess strength—a testing procedure previously shown reliable (intraclass correlation coefficient = 0.82-0.98) (Feiring et al., 1990). Participants were seated on the Biodex system and secured with padded straps around the thigh, pelvis, and torso to minimize accessory and compensatory movements during testing. The femoral condyle of the tested leg was aligned with the center of the Biodex axis of rotation per the manufacturer's instructions, with the cuff of the dynamometer lever arm secured just superior to the lateral malleolus of the tested leg. Participants were instructed to hold on to the handles located at the sides of the seat after which knee joint range of motion was determined and set to approximately 90°. To determine knee strength for the quadriceps and hamstring muscles, participants were instructed to perform three trials of knee extension and flexion, respectively, on each leg (six trials total) at velocities of 60, 120, and $180° \bullet s^{-1}$, with each trial consisting of 10 repetitions (total of 30 repetitions each leg). Peak torque normalized to body weight at each velocity for both legs of each participant was used in the statistical analyses.

Squat Jump. On a separate day, participants performed three squat jumps on a single force platform (Kistler, 9286AA, Switzerland)—a protocol which has demonstrated high reliability (coefficient of variation=3.3%) (Markovic et al., 2004). Due to participant time constraints, only ten (4 males, 6 females) of the 19 participants completed squat jump testing. After the participant's weight in Newtons (N) was determined, the force platform was zeroed. Each participant began the squat jump with feet shoulder width apart, toes pointed forward, and hands on hips (Impellizzeri et al., 2007). Keeping the hands on the hips reduces the influence of arm motion which allows for a better reflection of lower extremity function contributing to jump height and force production (Impellizzeri et al., 2007). Participants were then instructed to squat down to a 90° angle of knee flexion and remain stationary for 3 seconds before jumping off the force platform as fast as possible to attain maximal jump height—landing back on the force platform after performing each jump. If a countermovement was detected after static squatting and during jump initiation, the results were discarded and participants were asked to perform another trial. This procedure was implemented as a jump without a countermovement (i.e., squat jump) to minimize variability and measurement error when calculating jump height and jump execution variables, such as peak rate of force development (RFD) (Hori et al., 2009). One minute of rest between each repetition was given to each participant for recovery. BioWare® software (Kistler 2812A, Switzerland) was used for data collection (1202 Hz). Data was filtered (fourth-order Butterworth low-pass, 50 Hz cutoff frequency) and exported for each trial. Variable calculation was automated using the procedure described in Fitzgerald et al. (2017). Jump height and execution variables (i.e., peak and average RFD and peak force) were calculated. Jump height was calculated using the following equation developed by Moir et al. (2009): Jump height = (vertical velocity of center of mass at takeoff)^2 / (2x9.81). Peak force attained before takeoff was recorded. Peak RFD, which describes the ability to rapidly develop muscular force, was reported as the peak time derivative of the vertical force trace while average RFD was calculated by dividing peak force by time to peak force (Fitzgerald et al., 2017). Average jump height and execution values from the three trials were then used in the statistical analyses. As squat jump testing was completed on a single force platform (as opposed to dual force platforms), all right and left leg lean soft tissue mass measurements for each of the three respective analyses (i.e., total leg, total upper leg, compartmental leg) were summed prior to analysis.

Statistical Analyses

All data analyses were performed using SPSS version 24 (IBM Software, New York, USA). Pearson correlation coefficients examined the relationship between lean soft tissue mass measured using three different ROIs and (a) normalized peak torque at the three different angular velocities measured via isokinetic dynamometry and (b) normalized jump execution variables (average and peak RFD and peak force) and jump height measured via squat jump. The three ROIs examined were: (i) total leg and (ii) upper leg lean soft tissue mass measured in the total-body frontal DXA scanning view and (iii) compartmental (anterior/posterior) upper leg lean soft tissue mass measured in the lateral segmentation DXA scanning view. Cohen's criteria were used to categorize correlation strength (Cohen, 1988). As all correlation analyses were within-subject, and as correlation values were similar for males and females separately, all individuals were combined. Significance was set at $p<0.05$.

Results

Study participant characteristics are presented in Table 1. Correlation coefficients of (i) total leg, (ii) upper leg, and (iii) compartmental leg lean soft tissue mass measurements and isokinetic peak torque during extension and flexion at each of the three angular velocities are displayed in Table 2. Observations revealed compartmental leg lean soft tissue mass demonstrated similar correlations with peak torque at each angular velocity in comparison with total leg and upper leg lean soft tissue mass. Notably, of all the compartmental measurements, the right posterior (range: r = 0.526 to 0.835) and left anterior compartments (range: r = 0.556 to 0.721) demonstrated the highest correlations (all $p<0.05$). Although smaller, upper leg lean soft tissue mass also demonstrated significant correlations for extension (r = 0.503 to 0.584) and a majority of flexion (r = 0.449 to 0.795) measurements. Finally, total leg lean soft tissue mass was observed to have similar and significant correlations for extension (r = 0.497 to 0.591) and flexion (r = 0.463 to 0.803) when compared to upper leg and compartmental leg lean soft tissue mass measurements. Overall, the highest correlations for all three analyses (i.e., total leg, upper leg, and compartmental leg) with peak torque were generally observed at angular velocities of $60°\bullet s^{-1}$ and $120°\bullet s^{-1}$, with similar correlations observed for compartmental, upper leg, and total-leg ROIs (see Figure 1 [extension at $60°\bullet s^{-1}$] and Figure 2 [flexion at $120°\bullet s^{-1}$]). Cohen (9) suggests all correlation values are moderate (0.3 to 0.5) to large (0.5 to 1.0).

Table 3 displays correlations of total leg lean soft tissue mass, total upper leg lean soft tissue mass, and the sum of upper leg compartmental lean soft tissue mass of each leg (i.e., right + left anterior, right + left posterior) with jump height and jump execution variables. Data indicated that total leg (range of r = 0.830 to 0.940) and total upper leg (range of r = 0.824 to 0.953) measurements demonstrated significantly strong correlations with jump height (the primary outcome), average and peak RFD, and peak force. When comparing the upper leg compartments, the sum of the *posterior* right and left leg lean soft tissue mass measurements demonstrated higher correlations for each vertical jump variable (range of r = 0.750 to 0.951) compared to the sum of the *anterior* right and left leg lean soft tissue mass measurements (range of r = 0.582 to 0.798) (Table 3; Figure 3). Further, lean soft tissue mass in the total leg, total upper leg, and anterior and posterior compartments demonstrated higher correlations with jump height than with RFD or peak force. Similar correlations were observed between lean soft tissue mass measured using the aforementioned ROIs and average and peak RFD, with slightly higher correlations observed between lean soft tissue mass and peak force (Table 3). Finally, Figure 3 displays the similarly strong correlations of lean soft tissue mass measured using total-leg (r = 0.940), total upper leg (r = 0.953), and sum of anterior (r = 0.798) and sum of posterior (r = 0.951) compartmental leg ROIs with jump height. Cohen (9) suggests all correlation values are high (0.5-1.0).

Discussion

To our knowledge, this is the first study to assess the association of upper leg compartmental lean soft tissue mass measured using the lateral segmentation DXA scanning method with (a) peak torque measured via isokinetic dynamometry and (b) squat jump height/execution variables measured via jump mechanography and to compare this segmentation method to traditional DXA measurements of total and upper leg masses. The most important finding of this study was the moderate-to-strong correlations ($p<0.05$) observed between upper leg compartmental (i.e., anterior/posterior) lean soft tissue mass and isokinetic peak torque, jump height, and jump execution variables—associations similar to those observed for total-leg and upper leg lean soft tissue mass measurements. Our hypothesis was therefore supported by the observation that the lateral segmentation method for measuring anterior/posterior compartmental lean soft tissue mass is strongly correlated with muscle specific strength during an isokinetic task (Table 2) and demonstrates a strong relation with explosive strength during a jumping task (Table 3). These observations are important, as the lateral segmentation method could be utilized by sports medicine professionals to (a) examine athletes' compartmental lean soft tissue mass and muscle function in response to training or rehabilitation or (b) assess lean mass and functional imbalances that may increase athletes' injury or reinjury risk.

Currently, literature examining athletes reports a mixed relationship between muscle size (i.e., cross-sectional area, muscle volume) and strength (peak torque) for isokinetic concentric/eccentric maximal voluntary muscle contractions. Some studies (Akagi et al., 2014; Denadai et al., 2016) have reported low, non-significant correlations ($r = -0.33$ to 0.28) between these two variables, while others (Masuda et al., 2003) have observed significant ($p<0.05$) moderate correlations of quadriceps and hamstring muscle cross-sectional area (evaluated separately) with isokinetic peak torque of the knee extensors ($r = 0.54$-0.60) and flexors ($r = 0.54$-0.64), respectively. In the current study, moderate-to-strong positive correlations were observed between lean soft tissue mass and peak torque. Further, ipsilateral compartmental lean soft tissue mass demonstrated similar correlations across each of three isokinetic velocities of extension/flexion compared to total-leg and upper leg lean soft tissue mass measurements. This observation might be due to the fact that lateral compartmental lean soft tissue mass quantification using DXA includes not only knee extensor/flexor muscles in the respective anterior/posterior upper leg compartments but also additional muscles (e.g., adductors) that may contribute to isokinetic peak torque measurements. Further research is warranted to confirm this hypothesis in other athlete populations.

It is also noteworthy that the current study observed the highest correlations among all three lean soft tissue mass ROI contexts (total-leg, upper leg, compartmental leg) with isokinetic velocities of 60 and 120°•s^{-1} during flexion and 60°•s^{-1} during extension (Table 2, Figures 1 and 2). Although higher velocities (e.g., ≥180°•s^{-1}) have more specificity and transference to sports movements, lower velocities (e.g., 60 and 120°•s^{-1}) allow time for agonist/antagonist muscle (e.g., quadriceps/hamstrings) co-activation, thereby providing an in-depth analysis of specific muscle group strength and knee joint stabilization during knee extension/flexion (Aagaard et al., 1995; Aagaard et al., 1996). These observations therefore suggest that future studies use these two velocities to assess athletes' strength in association with compartmental, upper, and total-leg lean soft tissue mass—particularly to examine athletes' longitudinal changes in muscle function in response to training or rehabilitation programs.

The present study also observed strong positive correlations of lean soft tissue mass measured in all three lean soft tissue mass ROI contexts with squat jump variables. These observations are not only congruent with observations of a positive association between total-body and lower limb lean soft tissue mass with countermovement jump height (p<0.001, r=0.73) and peak power (p<0.001, r=0.74) noted by Stephenson et al. (2015) in the general population, but are also similar to previous studies assessing athletes (Bell et al., 2014; Jordan et al., 2015). These studies, using dual force platforms, observed a direct relationship between lean soft tissue mass measured using various lower extremity ROIs (e.g., upper leg, lower leg) and jump height and explosive strength. Therefore, the current study's observations are well supported by literature assessing the association between lean soft tissue mass and force production in athletic populations (Bell et al., 2014; Jordan et al., 2015). Finally, these observations are important, as they provide an additional method by which coaches and sports medicine professionals can assess not only region-specific lean mass and explosive strength separately, but also examine how these variables relate to muscle function—critical measures to monitor for the goal of optimizing sports performance, preventing lower extremity injury, and ensuring athletes' readiness to return to play following injury.

Finally, it should be noted that some variability in jump performance is unexplained by lean soft tissue mass measurements. In fact, literature (Aagaard & Thorstensson, 2008; Bell et al., 2014; Harridge et al., 1996; Lees et al., 2004; Lepley et al., 2017; Montgomery et al., 2012; Walsh et al., 2012) suggests that additional factors, such as neuromuscular control, muscular strength, muscle cross-sectional area, muscle fiber type, and limb and tendon length, among others, may be responsible for differences in force production and an individual's RFD. Therefore, although the lateral segmentation DXA scanning method utilized in the current study provides a more in-depth analysis of the distribution of lean soft tissue mass within the upper leg in relation to jump height and execution, other factors likely contribute to these jump measures.

Major strengths of the current investigation include: (a) the study population's large variation in body composition, with a BMI range of 19.1-32.1; (b) control of arm movement during the squat jump by instructing participants to place hands on hips, thereby removing arm swing influence on test results and better reflecting lower-limb muscle function; and (c) use of DXA to assess body composition. Limitations of the current study include a small sample size, use of a single force platform instead of a dual force platform, and lack of record pertaining to dominant leg. Additionally, a potential risk for false positive significant correlations was present due to the large number of correlations performed. However, Figures 1 and 2 show that the smaller ROIs demonstrated similar correlations to those of the larger ROIs (e.g., compartmental leg vs. total-leg lean soft tissue mass). Relatedly, because the current study was the first to examine the relationship of lean soft tissue mass in each region of interest (i.e., compartmental, upper, and total leg) and muscle specific strength (using isokinetic dynamometry), we felt it important to assess correlations at each of three velocities to determine the velocity demonstrating the highest correlations, and therefore multiple comparisons were performed. Finally, as a limitation of the DXA scanner, the post-scan analysis of the novel lateral segmented DXA scanning technique may not be capable of fully separating muscle compartments, thereby including additional muscles in either the anterior or posterior compartments (e.g., adductors).

In conclusion, this study observed an association between upper leg compartmental lean soft tissue mass measured utilizing the lateral segmentation DXA scanning method with (a) isokinetic peak torque and (b) squat jump height/execution—variables important in the cross-sectional and longitudinal assessment of sports performance relating to muscle function. The preceding associations were similar to those observed for total-leg and upper leg lean soft tissue mass. Therefore, the current study demonstrated the feasibility of utilizing this novel scanning method to provide a more comprehensive analysis of the association between lean soft tissue mass in smaller regions of interest and muscle specific strength and explosive strength.

Practical Applications

The current study observed moderate-to-high correlations of upper leg compartmental lean soft tissue mass with muscle specific and explosive strength in a healthy athlete population—similar correlations to those observed for total-leg and upper leg lean mass measurements. The quantification of upper leg compartmental lean soft tissue mass utilizing the lateral segmentation DXA scanning method—particularly in relation to muscle specific and explosive strength—is important in the examination of an athlete's relative muscle functionality. As such, this method may demonstrate future utility in assessing muscle functionality as it relates to sports performance, injury, or injury risk. More specifically, as contralateral and ipsilateral upper leg compartmental strength imbalances (particularly measured via isokinetic dynamometry) may increase an athlete's risk of lower extremity injuries (e.g., anterior cruciate ligament tear, hamstring strain) (Croisier et al., 2002; Impellizzeri et al., 2007), the lateral segmentation method—in conjunction with functional testing—may provide utility in detecting these compartmental imbalances. Relatedly, as Bell et al. (2014) stated, deficiencies in lean soft tissue mass may not only decrease force production but may also have implications for injury risk. However, as these researchers only assessed the relationship of contralateral leg lean mass and force production, it is important to also assess ipsilateral lean soft tissue mass, as significant ipsilateral asymmetries may increase athletes' injury risk. Therefore, information obtained while using the lateral segmentation method may allow strength and conditioning professionals, in addition to physical therapists, to develop more effective training and rehabilitation regimens to improve functionality of specific upper leg muscle groups, thereby optimizing athletes' performance and potentially reducing future injury risk.

Future research could compare the strength of relationship between upper leg compartmental lean soft tissue mass and (a) muscle specific strength and (b) explosive strength using a larger sample size and various athlete types to determine the optimal muscle functionality assessment method as it relates to ROI-specific lean soft tissue mass. Further, research is warranted to assess the utility of this lateral segmentation method in examining longitudinal changes in compartmental lean soft tissue mass in relation to muscle function in previously-injured athletes. Doing so may provide valuable insight into athletes' rehabilitation progress (e.g., pre- to post-), thereby allowing physical therapists to longitudinally track changes in compartmental lean soft tissue mass in response to rehabilitation. Therefore, this method may provide utility in the analysis of contralateral and ipsilateral lean mass imbalances—particularly in relation to muscle function—not only to ensure previously-injured athletes safely return to play following rehabilitation but also to optimize athletes' sports performance following return to play.

Table Legends

Table 1. Descriptive Participant Characteristics and Baseline Measurements

Table 2. Relationship of Unilateral Total, Upper, and Compartmental Leg Lean Soft Tissue Mass with Peak Torque Measurements

Table 3. Correlations of Total Leg, Total Upper Leg, and Compartmental Leg Lean Soft Tissue Mass with Double Leg Squat Jump Variables

Tables

Table 1. Descriptive Participant Characteristics and Baseline Measurements

	Total	Range
Participants (*n*)		
Males	9	
Females	10	
Age (yr.)	20.4±1.4	18-23
Body weight (kg)	73.8±17.0	55.2-102.4
Height (m)	1.8±0.1	1.6-1.9
Body Mass Index (kg/m^2)	23.6±3.8	19.1-32.1
Percent Body Fat (%)	16.2±4.1	8.3-22.1
Total Fat Mass (kg)	11.2±2.7	7.1-16.0
Total Lean Soft Tissue Mass (kg)	59.7±15.7	43.9-82.3

Age, body weight, height, body mass index, percent body fat, total fat mass, and total lean soft tissue mass are presented as mean ± SD.

Table 2. Relationship of Unilateral Total, Upper, and Compartmental Leg Lean Soft Tissue Mass with Peak Torque Measurements

	Extension			Flexion		
	$60°\bullet s^{-1}$	**$120°\bullet s^{-1}$**	**$180°\bullet s^{-1}$**	**$60°\bullet s^{-1}$**	**$120°\bullet s^{-1}$**	**$180°\bullet s^{-1}$**
Total Leg						
Right	0.591**	0.497*	0.539*	0.799**	0.803**	0.557*
Left	0.509*	0.507*	0.532*	0.463*	0.738**	0.490*
Upper Leg						
Right	0.584**	0.503*	0.573*	0.764**	0.795**	0.599**
Left	0.549*	0.538*	0.567*	0.449	0.744**	0.479
Compartmental Leg						
Right Anterior	0.545*	0.437	0.502*	-	-	-
Right Posterior	-	-	-	0.791**	0.835**	0.526*
Left Anterior	0.556*	0.706**	0.721**	-	-	-
Left Posterior	-	-	-	0.533*	0.743**	0.470*

[a] Strength measurements were normalized to body weight, $Nm{\cdot}kg^{-1}$

* Correlation is significant at p<0.05

** Correlation is significant at p<0.01

Table 3. Correlations of Total Leg, Total Upper Leg, and Compartmental Leg Lean Soft Tissue Mass with Double Leg Squat Jump Variables [a]

Lean Soft Tissue Mass Measure	Jump Height	RFD (avg)	RFD (peak)	Peak Fz
Total Leg	0.940**	0.839**	0.830**	0.903**
Total Upper Leg	0.953**	0.824**	0.862**	0.915**
Compartmental Leg				
Anterior Sum (Right+Left)	0.798**	0.711*	0.651*	0.582
Posterior Sum (Right+Left)	0.951**	0.750*	0.844**	0.916**

[a] Strength measurements were normalized to body weight, $N \cdot kg^{-1}$

Abbreviations: RFD (avg), average rate of force development; RFD (peak), peak rate of force development; Peak Fz, peak force.

* Correlation is significant at the *p*<0.05 level.

** Correlation is significant at the *p*<0.01 level.

Figures

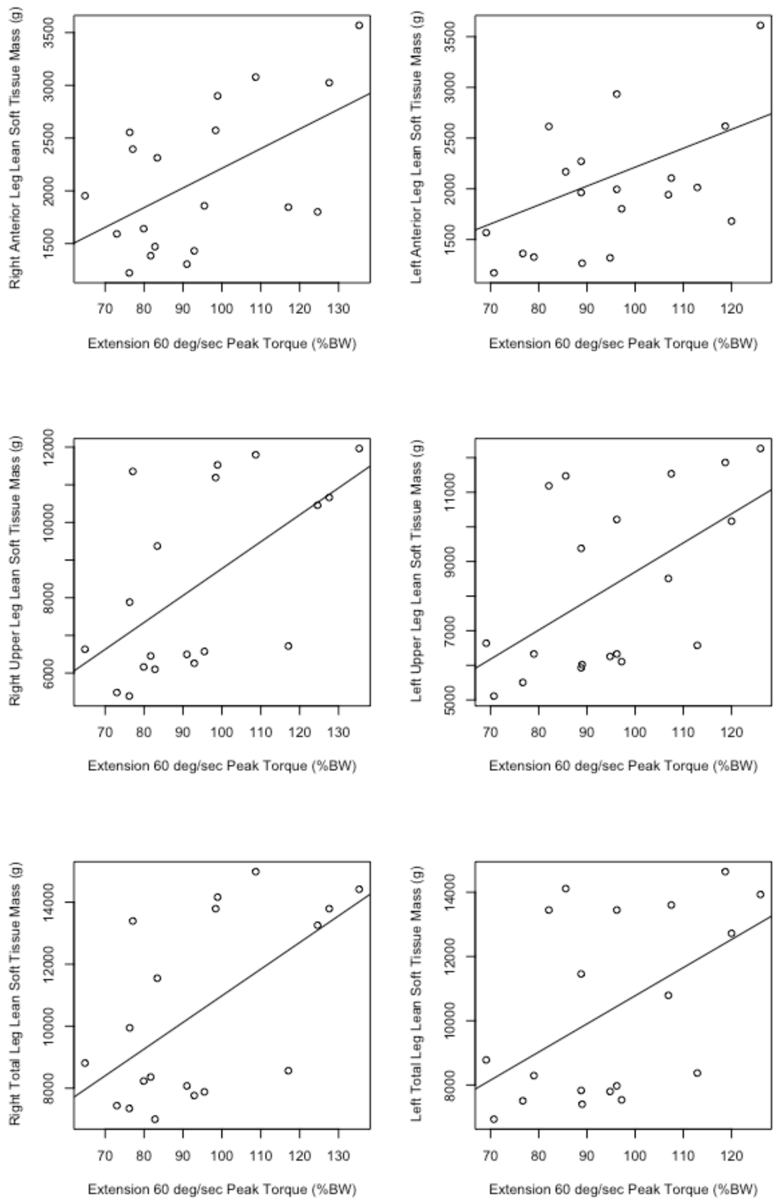

Figure 1. Relationship of Lean Soft Tissue Mass Using Three Separate ROIs and Strength During Extension at $60° \bullet s^{-1}$ [Note: %BW indicates absolute peak torque values normalized to body weight and expressed as a percentage]. ROIs = regions of interest; BW = body weight.

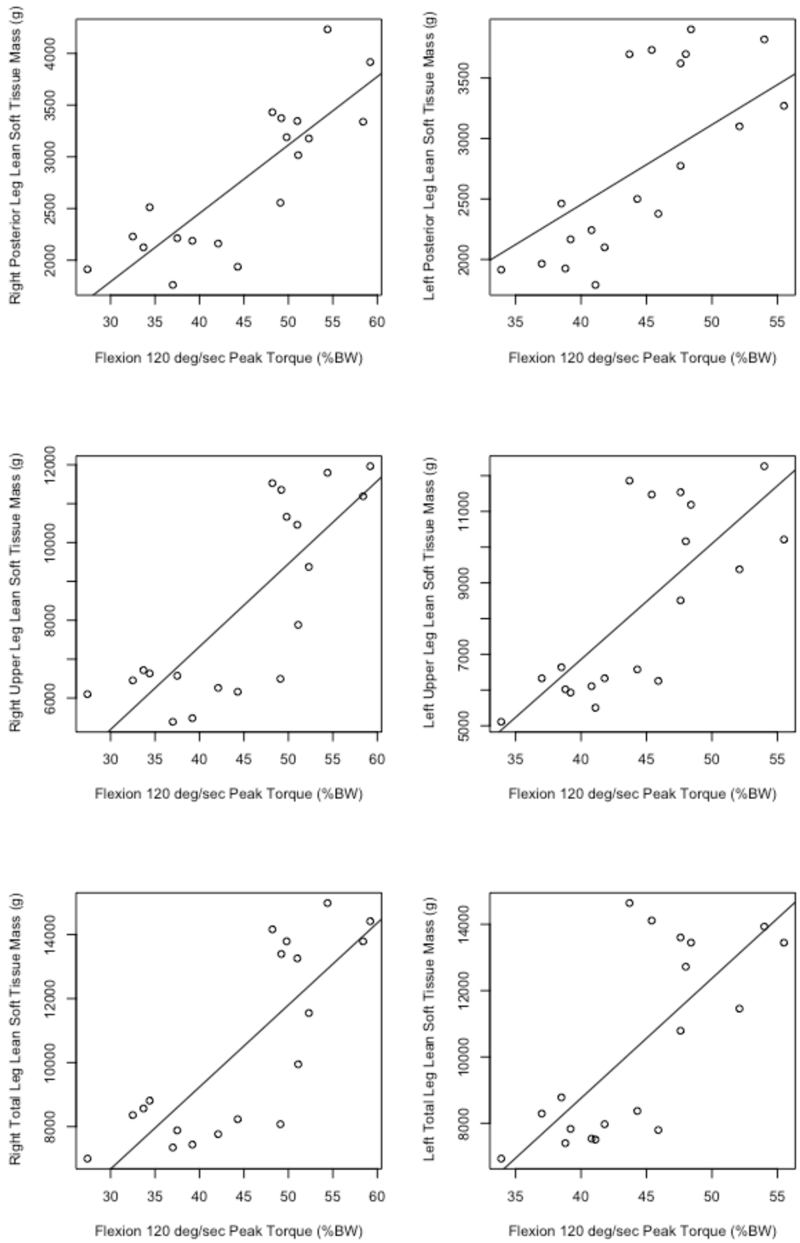

Figure 2. Relationship of Lean Soft Tissue Mass Using Three Separate ROIs and Strength During Flexion at 120°•s^{-1} [Note: %BW indicates absolute peak torque values normalized to body mass and expressed as a percentage]. ROIs = regions of interest; BW = body weight.

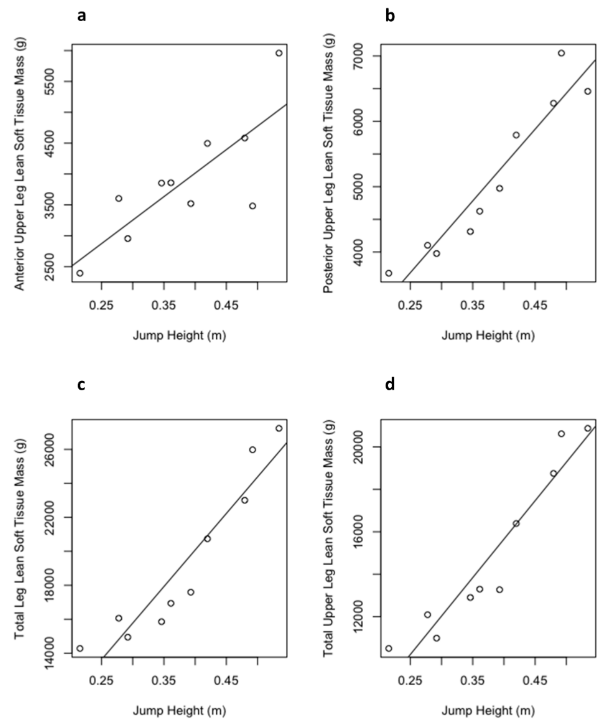

Figure 3. Relationship of Lean Soft Tissue Mass Using Three Separate ROIs and Vertical Jump Height. ROIs = regions of interest.

CHAPTER 5. LEAN MASS, STRENGTH, AND FORCE PRODUCTION DEFICITS IN ACL-RECONSTRUCTED ADOLESCENT FEMALE ATHLETES FOLLOWING RETURN TO SPORT

Lean Mass, Strength, and Force Production Deficits in ACL-Reconstructed Adolescent Female Athletes Following Return to Sport

Authors: Christiana J. Raymond-Pope, M.S.[1], Donald R. Dengel, Ph.D.[1,5], John S. Fitzgerald, Ph.D.[3], Bradley J. Nelson, M.D.[4], Tyler A. Bosch, Ph.D.[2]

[1]Laboratory of Integrative Human Physiology, School of Kinesiology, University of Minnesota, Minneapolis, MN 55455
[2]College of Education and Human Development, University of Minnesota, Minneapolis, MN 55455
[3]Department of Education, Health, and Behavior Studies, University of North Dakota, Grand Forks, ND 58202
[4]Department of Orthopaedic Surgery, University of Minnesota Medical School, Minneapolis, MN 55455
[5]Department of Pediatrics, University of Minnesota Medical School, Minneapolis, MN 55455

Key Words: Anterior cruciate ligament (ACL), dual X-ray absorptiometry (DXA), isokinetic dynamometry, squat jump

Publication Reference: Raymond-Pope, CJ, Dengel, DR, Fitzgerald, JS, Nelson, BJ, Bosch, TA. Lean Mass, Strength, and Force Production Deficits in ACL-Reconstructed Adolescent Female Athletes Following Return to Sport. Submitted to *Journal of Athletic Training* 2019.

Disclosures: The authors declare there is no competing or conflict of interest associated with this research study. Christiana J. Raymond-Pope prepared the first draft of the manuscript without any associated honorarium, grant, or other form of payment to produce the manuscript.

Funding Source: This study was supported by the 2015 Marco Cabrera Student Research Award from the North American Society of Pediatric Exercise Medicine (NASPEM).

Summary

Context: Previous literature reports that contralateral (inter-limb) upper-leg muscle and strength asymmetries increase secondary anterior cruciate ligament (ACL) injury risk following ACL reconstruction (ACLR). However, a more detailed assessment of contralateral and ipsilateral (intra-limb) relative muscle functionality is needed. **Objective:** Evaluate different measures of muscle function, including lean mass (LM), isokinetic peak torque (PkTq), and explosive strength, between athletes with prior ACLR and matched controls. **Design:** Case-control study. **Setting:** University research laboratory. **Patients or Other Participants:** Twenty-four female athletes, 12 with prior ACLR and 12 controls, were matched by age (16.4±0.9 vs. 16.4±1.0 yrs.), body mass index (23.2±2.1 vs. 23.2±2.7 kg/m^2), and sport. **Main Outcome Measures:** Three dual X-ray absorptiometry (DXA) scans (1 total-body, 2 lateral leg) measured total and segmental body composition. Isokinetic dynamometry measured knee extensor/flexor PkTq. Squat jumps on force plates measured explosive strength. Paired t-tests assessed total-leg, upper-leg, and upper-leg compartmental LM, PkTq, and force production differences within- and between-groups. Linear regression assessed LM's relationship with PkTq and force for each leg. **Results:** While no significant LM differences were observed between ACLR and control groups, the ACLR involved leg demonstrated lower total LM (7.13±0.75 vs. 7.43±0.99kg; p=0.004), anterior upper-leg LM (1.49±0.27 vs. 1.61±0.23kg; p=0.007), and posterior upper-leg LM (1.90±0.19 vs. 2.02±0.21kg; p=0.036) vs. the non-involved leg. PkTq in the ACLR involved leg (1.36±0.31; 1.06±0.27; 0.97±0.19Nm/kg) was lower vs. the non-involved leg (1.71±0.36; 1.24±0.33; 1.04±0.15Nm/kg; p<0.001 to 0.0218) for extension at

60 and 120°/sec and flexion at 60°/sec and vs. controls' 'matched' leg (1.77±0.40Nm/kg; *p*=0.0097) for extension at 60°/sec. Similarly, ACLR involved leg peak force (296±45N) was lower vs. the non-involved leg (375±55N; *p*<0.001) and vs. the 'matched' control leg (372±88N; *p*=0.0152). **Conclusions:** One-year post-ACLR, adolescent female athletes' involved leg demonstrated significant LM and muscle function deficits. These differences may increase the risk for secondary ACL injury.

Introduction

Anterior cruciate ligament (ACL) injuries are among the most severe lower extremity injuries suffered by athletes, with up to 80% occurring without contact (Joseph et al., 2013; Renstrom et al., 2008). Females have demonstrated a 2- to 6-fold greater ACL tear incidence than males in sex-comparable sports requiring cutting and jumping (Beynnon et al., 2014; Gornitzky et al., 2016; Paterno et al., 2012). Further, athletes' secondary ACL injury rates (in either the involved or non-involved leg) are as high as 30% within 2 years after return-to-sport (RTS) (Paterno et al., 2014; Wiggins et al., 2016). Studies have reported athletes post-ACL reconstruction (ACLR) to demonstrate dysfunctional lower extremity biomechanics and contralateral force asymmetries during double- and single-leg landing and jumping tasks (Goerger et al., 2014; Hewett et al., 2005; Ithurburn et al., 2015; Palmieri-Smith & Lepley, 2015), with quadriceps strength and muscle mass asymmetries also noted (Konishi et al., 2011; Schmitt et al., 2012). Given the high secondary ACL injury incidence, exclusive contralateral strength and hop-test asymmetry assessment at the time of RTS may not be adequate to ensure athletes' readiness to RTS. Instead, assessing lean mass's relationship with muscle-specific and explosive strength (i.e., time-restricted force production) may provide greater insight into athletes' relative muscle functionality (i.e., strength/force per unit lean mass) post-ACLR.

To date, studies have separately investigated muscle-specific strength via isokinetic dynamometry and explosive strength via vertical jumping in ACLR athletes, with fewer studies having examined muscle mass/size. Studies using isokinetic dynamometry have reported quadriceps strength asymmetries of 14% persisting up to 12 months post-ACLR

(Risberg & Holm, 2009; Schmitt et al., 2012). Other studies employing magnetic resonance imaging (MRI) have reported significant contralateral quadriceps muscle volume (MV) asymmetries. In addition, significant differences in isokinetic extensor peak torque produced per unit of quadriceps MV between legs in physically active ACLR adults vs. controls has been reported (Konishi et al., 2007, 2011). Researchers have also reported force production asymmetries of ~15% in athletes with prior ACLR during the takeoff (Jordan et al., 2015; Paterno et al., 2007) and landing (Paterno et al., 2007, 2011) phases of the drop vertical jump (DVJ) and countermovement jump (CMJ). However, the DVJ and CMJ incorporate the stretch-shortening cycle which potentially masks neuromuscular asymmetries (Bobbert et al., 1996). Alternatively, the squat jump (SJ) requires athletes to exert force through a concentric-only contraction phase (a quadriceps-dominant movement), which may better assess underlying neuromuscular asymmetries masked by the stretch-shortening cycle (Bobbert et al., 1996; Byrne & Eston, 2002). However, there is limited research (Jordan et al., 2015) examining SJ force asymmetries in ACLR athletes, particularly in relation to lean mass.

Dual X-ray absorptiometry (DXA) is currently considered the *'gold standard'* body composition assessment method (Shultz & Schmitz, 2018) and may have great utility in assessing lean mass's relationship with muscle-specific and explosive strength. Recently, a lateral view DXA scanning method demonstrated accuracy in analyzing upper-leg compartmental lean mass (Raymond et al., 2017), allowing for region-specific (e.g., quadriceps/hamstrings) lean mass quantification. These measurements subsequently demonstrated moderate-to-strong associations with isokinetic peak torque and SJ force production (Raymond-Pope et al., 2018). Notably, upper-leg compartmental lean mass assessments address recent calls by researchers (Bishop et al., 2018; Shultz & Schmitz, 2018) for more detailed body composition analysis methods to examine how body composition contributes to dysfunctional lower extremity biomechanics and reinjury risk.

This pilot study's purpose was therefore to evaluate different measures contributing to muscle function in adolescent female athletes one-year post-ACLR vs. individually-matched control athletes. Specifically, we sought to: (a) examine lean mass differences (i) between the involved (INV) and non-involved (NINV) legs of ACLR adolescent female athletes and (ii) between individually-matched legs of ACLR female athletes and healthy female athlete controls; and (b) examine the relationship between lean mass, isokinetic knee extensor/flexor peak torque, and explosive strength to determine the relative muscle functionality in ACLR female athletes' legs. We hypothesized ACLR female athletes would demonstrate lower: (a) lean mass for each region of interest (ROI; compartmental, upper, total-leg); (b) isokinetic peak torque; and (c) force in the INV vs. NINV leg and matched control leg.

Methods

Subjects

Twenty-four female athletes, 12 with previous ACLR and 12 healthy controls, participated in this pilot study. We recruited ACLR female athletes from local orthopedic centers and each ACLR female athlete was individually matched to a healthy female athlete control by age (16.4±0.9 vs 16.4±1.0 yrs.), body mass index (23.2±2.1 vs 23.2±2.7 kg/m^2), and sport (alpine skiing *n*=6, basketball *n*=4, gymnastics *n*=2). The ACLR group's mean postoperative period was 13.1±1.7 months. ACLR female athletes were included in the study if they were 15-18 years old, suffered a unilateral ACL injury, had ACLR within 10-16 months before testing, and had been cleared to RTS. ACLR female athletes were excluded if they had ACL injury on both legs. Female controls were included if they matched with a specific ACLR athlete, were athletes currently participating on a high school sports team, were 15-18 years old, and had no history of ACL injury. Controls were excluded if they had a significant lower-body injury that led to substantial time off from sport 6 months before testing. This study's protocol was approved by the University's Institutional Review Board. Written informed consent was obtained from all athletes (and guardians, when participants were <18 years).

DXA Scans. All athletes were instructed to abstain from vigorous exercise at least 24 hours prior to testing and to come having fasted for at least 4 hours prior to DXA scans. Each athlete's height and weight were measured using an electronic scale and wall-mounted stadiometer (Model S100; Ayrton Corp., Prior Lake, MN). All athletes were screened for pregnancy before undergoing DXA scans and wore light, metallic-free clothing during scans. Total body composition was measured using standard total-body frontal DXA scanning procedures (GE Healthcare Lunar) in the supine position on a GE Lunar iDXA (iDXA, General Electric Medical Systems, Madison, WI, USA). Post-scan analyses were performed using enCore™ software (platform version 16.3, General Electric Medical Systems, Madison, WI, USA). After the total-body scan, athletes received two DXA leg scans (one for each leg) using the full-body scan mode to quantify fat mass and lean mass in the lateral view. These lateral DXA scanning procedures have previously been described by Raymond et al. (2017). Following scan completion, a two-dimensional computer image was generated for post-scan analysis. The post-scan image was then segmented to assess lean mass within three ROIs: (i) total-leg in the frontal view; (ii) upper-leg in the frontal view; and (iii) anterior/posterior upper-leg compartments in the lateral view. All segmental analyses have been described previously (Raymond et al., 2017; Raymond-Pope et al., 2018) and have demonstrated high inter- and intra-rater reliability (coefficients of variation < 4.8%).

Isokinetic Dynamometry. Following DXA scans, all athletes performed standard same-day muscle testing procedures per previously described methods (Raymond-Pope et al., 2018) for unilateral right and left knee extension and flexion strength assessments on a Biodex System 3 Pro (Biodex Medical Systems, Shirley, NY) isokinetic dynamometer. Prior to testing, athletes completed a warm-up consisting of 5 minutes of jogging on a treadmill at a self-selected speed. To determine knee extensor and flexor torque, athletes performed two trials of knee extension and flexion on each leg (four trials total) at 60 and 120°/sec, with each trial consisting of 10 repetitions and one minute of rest between each trial. For all ACLR and control group athletes, the right leg was always tested first, followed by testing of the left leg. Peak torque normalized to body mass at each velocity for both legs was used in the statistical analyses.

Squat Jump. Following isokinetic dynamometry testing, athletes were given 15 minutes of rest, after which they performed three SJs on dual force platforms (Kistler, 9286AA, Switzerland). A SJ without countermovement was chosen to minimize variability and measurement error when calculating jump height/execution variables (e.g., peak and average rate of force development [RFD]) (Hori et al., 2009). Each athlete began the SJ with feet shoulder width apart, toes pointed forward, and hands on hips to reduce the influence of arm movement on jump height/execution, therefore better reflecting lower extremity function (Impellizzeri et al., 2007; Markovic et al., 2004). Athletes squatted to a 90° angle of knee flexion and remained stationary for 3 seconds before jumping off force plates as fast as possible to attain maximal jump height. One minute of rest between repetitions was given. BioWare® software (Kistler 2812A, Switzerland) was used for data collection (1202 Hz). Data were filtered (fourth-order Butterworth low-pass, 50-Hz cutoff frequency) and exported for each trial. Variable calculation was automated using the procedure described by Fitzgerald et al. (2017). Double-leg and between-leg jump height and execution variables (peak force, peak and average RFD, starting/acceleration gradients) were calculated using the same takeoff time. Jump height was calculated using the following equation (Moir et al., 2009): Jump height = [(vertical velocity of center of mass at takeoff)^2/(2x9.81)]. The jump height ratio for each group's legs (i.e., involved/noninvolved; matched/contralateral) was then calculated. Due to contralateral leg differences in weight transfer in the squat position, each leg's starting velocity for each athlete was corrected to zero for standardization. This variable, although theoretical, considers body mass and evaluates each leg's relative contribution to total jump height. Peak force attained before takeoff was recorded. Peak and average RFD were calculated per Fitzgerald et al. (2017). Starting gradient (half peak force/time to half peak force) and acceleration gradient (half peak force/[time to peak force – time to half peak force]) were also calculated (Fitzgerald et al., 2017). Average jump height and execution values from the three trials were used in statistical analyses.

Statistical Analyses

All data analyses were performed using RStudio (Version 1.0.143). Paired t-tests assessed total and segmental lean mass, isokinetic extensor and flexor peak torque, and force production mean differences within the ACLR (INV vs. NINV legs) and control (matched vs. contralateral legs) groups and between individually-matched ACLR and control adolescent female athletes. Each ACLR athlete's INV and NINV legs were matched to their matched-control's legs, termed "matched leg" and "contralateral leg," respectively. Briefly, if an ACLR athlete had ACL reconstruction on her right leg, this leg was termed "INV" for ACLR athletes and "matched leg" for controls, with the contralateral leg termed the "NINV" leg for ACLR athletes and "contralateral leg" for controls. Primary outcome variables were analyzed according to an α level of 0.05, including: within- and between-group anterior and posterior lean mass measurements; isokinetic peak torque at 60°/sec; and SJ height and peak force. Secondary outcome variables were analyzed according to an adjusted α level of 0.007 (p=0.05/7), including: within- and between-group upper-leg and total-leg LM measurements; isokinetic peak torque at 120°/sec; RFD; starting gradient (early-phase RFD); acceleration gradient (late-phase RFD); and jump height ratio. Effect sizes were calculated as Cohen's *d* with magnitude interpreted as follows (Hopkins et al., 2009): 0.0-0.2 = trivial, 0.2-0.6 = small, 0.6-1.2 = moderate, 1.2-2.0 = large, >2.0 = very large. When required, a Wilcoxon sign-rank test was used for non-parametric data and reported as Pearson's *r*, with magnitude interpreted as follows

(Hopkins et al., 2009): 0.1-0.3 = small, 0.3-0.5 = moderate, 0.5-1.0 = large. Following the above statistical analyses, a sub-analysis examining lean mass asymmetry differences between ACLR and control groups were assessed using the following limb symmetry index (LSI) calculations: [ACLR LSI = (INV – NINV) / ((1/2)*(INV + NINV)) x 100%; Control LSI = (matched – contralateral) / ((1/2)*(matched + contralateral)) x 100%] . Finally, linear regression assessed (a) compartmental lean mass vs. isokinetic extensor/flexor peak torque and (b) total-leg lean mass vs. peak force of each leg. The slope (*m*) and coefficient of determination (R^2) were calculated for each leg. The three lean mass ROIs examined were: (i) total-leg and (ii) upper-leg measured in the total-body frontal DXA scanning view and (iii) compartmental (anterior/posterior) upper-leg measured in the lateral DXA scanning view. Significance was set at $p<0.05$ for linear regression analyses.

Results

Table 1 displays body composition measurements of ACLR adolescent female athlete's INV and NINV legs, along with the mean difference (±SD) of measurements between legs of the ACLR and control groups. No body composition differences were observed between ACLR and control groups for any ROI. However, the ACLR INV leg vs. NINV leg demonstrated significantly lower total-leg lean mass and fat mass, upper-leg lean mass, and anterior and posterior upper-leg lean mass. No significant mean differences in lower extremity body composition were observed between legs of controls (Table 1). Effect sizes for anterior, posterior, upper-leg, and total-leg lean masses were -0.47, -0.57, -0.48, and -0.31, respectively, for ACLR INV vs. NINV legs, and -0.22, -0.31, -0.66, and -0.43, respectively, when comparing ACLR vs. control groups' LSI. Figure 1 displays results of anterior (Panels A&B) and posterior (Panels C&D) compartmental LSI calculations, and Figure 2 presents upper-leg (Panels A&B) and total-leg (Panels C&D) LSI calculation results.

Table 2 displays isokinetic peak torque measurements for knee extension and flexion within (i.e., between legs) and between ACLR and control groups. Peak torque was significantly lower in ACLR INV vs. NINV legs for extension at 60°/sec (d = -0.98) and 120°/sec (d = -0.57) and for flexion at 60°/sec (d = -0.44). Between ACLR and control groups, peak torque was significantly lower in ACLR INV leg vs. controls' 'matched' leg for extension at 60°/sec (d = -1.08). No significant differences were observed between the ACLR NINV leg vs. controls' 'contralateral' leg (d = -0.35 to 0.25) (Table 2).

Tables 3 and 4 present SJ between-leg and double leg measurement comparisons, respectively. Peak force was significantly lower in the ACLR INV leg vs. the NINV leg (r = -0.62) and between the ACLR INV leg vs. controls' 'matched' leg (r = -0.46). However, no significant (d=0.13) difference in peak force was observed between the ACLR NINV leg vs. controls' 'contralateral' leg. After adjustment, no significant differences were observed for all remaining SJ variables within the ACLR group and between ACLR vs. control groups (d = -0.33 to -0.32; r = -0.35 to -0.13). Regarding between-group double-leg comparisons, only the jump height ratio was significantly lower in the ACLR (INV/NINV) vs. control group (matched/contralateral) (d= -1.24).

Linear regression analysis for lean mass and isokinetic peak torque revealed a smaller slope between anterior lean mass and peak torque of extension at 60°/sec for ACLR participants (INV: m=0.03, R^2=0.13, p=0.24; NINV: m= -0.01, R^2=0.24, p=0.11) versus controls (matched: *m*=0.04, R^2=0.16, *p*=0.20; contralateral: *m*=0.05, R^2=0.36, *p*=0.04) (Figure 3, Panel A). Conversely, the association between posterior lean mass and isokinetic peak torque of flexion at 60°/sec was similar between ACLR (INV: *m*=0.04, R^2=0.46, *p*=0.02; NINV: *m*=0.02, R^2=0.18, *p*=0.18) and controls (matched: *m*=0.03, R^2=0.52, *p*=0.01; contralateral: *m*=0.03, R^2=0.42, *p*=0.02) (Figure 3, Panel B). Linear regression analysis for total-leg lean mass and peak force during the SJ revealed that the association for each leg was weaker for ACLR participants (INV: *m*=0.02, R^2=0.13, *p*=0.25; NINV: *m*=0.03, R^2=0.25, *p*=0.10) compared to matched control participants (matched: *m*=0.06, R^2=0.40, *p*=0.03; contralateral: *m*=0.06, R^2=0.38, *p*=0.03) (Figure 4).

Discussion

To our knowledge, this is the first study to assess contralateral asymmetries of (a) DXA-measured lateral view upper-leg compartmental lean mass, (b) isokinetic peak torque, and (c) SJ-measured force production in ACLR adolescent female athletes following RTS. Deficits in lean mass, isokinetic extensor peak torque, and SJ peak force production were observed in ACLR athletes' INV leg in comparison to their NINV leg. Further, lower peak torque and force were produced per unit of lean mass in both ACLR legs in comparison to individually-matched controls' legs. These observations indicated residual impairments in ACLR adolescent female athletes' lean mass and function despite RTS clearance. Observations may provide clinicians with more detailed information regarding relative muscle functionality one-year post-ACLR and potentially inform training/rehabilitation program development.

Lean Mass Comparisons

Supporting our first hypothesis, significant contralateral lean mass deficits were observed across all ROIs (compartmental, upper-leg, total-leg) in ACLR adolescent female athletes' INV leg compared to their NINV leg. These observations were similar to asymmetries previously reported for frontal view upper-leg lean mass measured by DXA (Jordan et al., 2015) and quadriceps MV measured by MRI (Konishi et al., 2007; Konishi et al., 2011). Although no significant lean mass mean differences were observed between our study's ACLR and control groups, this observation was similar to that made by Konishi et al. (2011). It is noteworthy, however, that our study's ACLR group demonstrated greater LSI values in upper- (effect size = -0.66; $p<0.001$) and total-leg (effect size = -0.43; $p=0.004$) lean mass compared to controls (Figure 2).

Functional Comparisons

Isokinetic Dynamometry Testing. Confirming our second hypothesis, ACLR adolescent female athletes demonstrated significant small to moderate isokinetic extensor peak torque deficits of ~20% and 15% in the INV leg at velocities of 60 and 120°/sec, respectively, compared to their NINV leg. Additionally, ACLR adolescent female athletes demonstrated significantly lower (~23%) extensor peak torque at 60°/sec vs. control's 'matched' leg. These observations indicated INV leg quadriceps weakness and are similar to prior studies examining isokinetic and isometric strength (Andersen et al., 2002; Cardone et al., 2004; Konishi et al., 2007; Konishi et al., 2011; McHugh et al., 2002). These studies cited contralateral quadriceps asymmetry averages of 23% and 14% within 6 and 12 months post-ACLR, respectively, as a primary impairment following ACLR (Risberg

& Holm, 2009; Schmitt et al., 2012) and which may contribute to secondary ACL injury risk following RTS (Grindem et al., 2016).

Squat Jump Testing. Our third hypothesis was supported as we observed significant moderate to large force production deficits in ACLR adolescent female athletes' INV leg of approximately 21% compared to their NINV leg and 20% in comparison to controls' 'matched' leg during the takeoff phase of a SJ. Previously, during the takeoff phase of a DVJ, Paterno et al. (2007) reported female athletes (mean age: 20.7±2.5 yrs.) 2 years post-ACLR produced ~15% lower force in the INV leg in comparison to the NINV leg and ~21% lower force compared to both legs of controls (all p=0.03). In a recent case-control study of elite alpine skiers (age range: 21-30.5 yrs.), Jordan et al. (2015) reported force production (i.e., impulse) LSI differences between ACLR and control groups during the CMJ's concentric phase (from squat position to jump takeoff; 6.5% vs. 0.5%; p<0.05) and the second half of the SJ's concentric phase right before takeoff (8.8% vs. -1.0%; p<0.05). Notably, these are movement phases which primarily use the quadriceps to generate force. Results from this study as well as previous research (Chmielewski et al., 2002; Hewett et al., 2005; Schmitt et al., 2012; Wiggins et al., 2016) imply that compensatory loading is placed upon the NINV leg, thereby increasing secondary *contralateral* (NINV) leg ACL injury risk. In addition, there is a decrease in the stimulus to strengthen the INV leg's quadriceps, resulting in sustained quadriceps weakness. Interestingly, we also observed a trend toward double-leg peak RFD differences between the ACLR and control groups during the SJ. Finally, we observed a lower SJ jump height ratio of ACLR athletes' legs vs. controls' legs, which is the first observation of this difference that we know of in any athlete population. Further research is warranted to investigate these novel observations.

Lean Mass vs. Functional Assessments. When examining the relationship between leg lean mass and functional measurements, our study's ACLR adolescent female athletes' INV and NINV legs demonstrated significant dysfunction vs. controls' 'matched' and 'contralateral' legs, respectively. During isokinetic testing, ACLR adolescent female athletes' legs produced less extensor peak torque per unit of anterior compartmental lean mass, which is similar to that of Konishi et al. (2011). However, while no lean mass differences were observed in our study between the ACLR INV leg and controls' 'matched' leg for any ROI, the INV leg demonstrated significant extensor peak torque deficits. When assessing the relationship between total-leg lean mass and force production during the SJ, both ACLR legs produced less force per unit of total-leg lean mass compared to controls' legs. Unlike both legs of controls, no significant linear relationship was observed between total-leg lean mass and force in the ACLR INV and NINV legs.

The preceding observations suggest isokinetic peak torque and SJ-measured force production deficits may be only partially explained by lean mass. In fact, other neuromechanical variables, in addition to lean mass, may be contributing to the relative muscle dysfunction observed in adolescent female athletes' legs following ACLR. Researchers have suggested arthrogenic muscle inhibition as a neural mechanism which may prevent full quadriceps activation by decreasing motor unit recruitment and firing frequency during quadriceps muscle contraction (Kuenze et al., 2014; Johnson et al., 2018). This mechanism may ultimately contribute to sustained quadriceps weakness. Finally, it can also not be ruled out that psychological factors related to levels of motivation and confidence, expectations, and fear of re-injury may also affect ACLR athletes' rehabilitation, training, and RTS outcomes (Ardern et al., 2013; Sonesson et al., 2017).

This pilot study's strengths included: (a) the matched case-control study design; (b) control of arm movement during the SJ by requiring participants to place hands on hips; (c) use of the *gold standard* DXA to assess body composition; and (d) use of two force platforms to measure force produced by each leg. The small sample size represented the study's main limitation. It should also be noted that the DXA scanner may not have been fully capable of entirely separating muscle compartments in the post-scan analysis when using the lateral segmentation DXA scanning method. This limitation may have allowed additional muscles (e.g., adductors) to be included in the anterior or posterior compartments. Regardless, this lateral segmentation method has demonstrated accuracy and reliability in assessing compartmental lean mass (Raymond et al., 2017).

Conclusion

We observed significant (a) DXA-measured total-, upper-, and compartmental-leg lean mass, (b) isokinetic extensor peak torque, and (c) SJ peak force asymmetries to persist in adolescent female athletes' INV leg one-year post-ACLR. Additionally, we observed relative muscle dysfunction in *both* INV and NINV legs when assessing the relationship between lean mass and the preceding functional assessments. These observed asymmetries and relative muscle dysfunction are important for clinicians to consider when designing individualized rehabilitation and training programs prior to and following RTS, respectively, to improve outcomes post-RTS and to decrease athletes' secondary ACL injury risk. Briefly, clinicians might consider training and routinely testing specific muscles (e.g., quadriceps) and explosive movements (e.g., vertical jumping) to reduce contralateral and ipsilateral asymmetries in lean mass and force production during rehabilitation and post-RTS. Future studies in other ACLR athlete populations are warranted to: (a) examine the relationship between lean mass and muscle-specific and explosive strength using a larger sample size; and (b) longitudinally assess how the preceding relationships change throughout the rehabilitation process and following athletes' RTS.

Table Legends

Table 1. Mean (±SD) Body Composition Comparisons in Three ROI Contexts Within ACLR and Within Control Groups

Table 2. Mean (±SD) Isokinetic Dynamometry Measures for Matched vs. Contralateral Legs of ACLR and Control Groups

Table 3. Mean (±SD) Between-Leg Squat Jump Comparisons Within and Between ACLR and Control Groups

Table 4. Mean (±SD) Double Leg Squat Jump Measures Between ACLR and Control Groups

Tables

Table 1. Mean (±SD) Body Composition Comparisons in Three ROI Contexts Within ACLR and Within Control Groups

Measures	ACLR INV	ACLR NINV	Mean of Differences (ACLR)	*p*-value	CON Matched	CON Contralateral	Mean of Differences (CON)	*p*-value
Total Leg								
Total Mass (kg)	11.74±1.48	11.91±1.70	-0.16	0.183	12.09±1.83	12.05±1.77	0.04	0.716
Lean Mass (kg)	7.13±0.75	7.43±0.99	-0.30	0.004[a]	7.54±1.00	7.50±0.94	0.04	0.649
Fat Mass (kg)	4.17±0.94	4.02±0.91	0.15	0.033[a]	4.05±1.08	4.06±1.08	0.00	0.978
Upper-Leg								
Total Mass (kg)	8.60±1.23	8.90±1.35	-0.31	0.001[a]	8.99±0.43	8.89±1.36	0.10	0.200
Lean Mass (kg)	5.30±0.62	5.66±0.75	-0.36	<0.001[a]	5.79±0.74	5.70±0.74	0.09	0.094
Fat Mass (kg)	3.08±0.80	3.02±0.78	-0.07	0.069	2.97±0.83	2.95±0.84	0.02	0.454
Compartmental								
Anterior								
Total Mass (kg)	2.22±0.43	2.33±0.35	-0.10	0.125	2.23±0.44	2.30±0.44	-0.07	0.130
Lean Mass (kg)	1.49±0.27	1.61±0.23	-0.13	0.007[a]	1.55±0.27	1.59±0.26	-0.04	0.249
Fat Mass (kg)	0.67±0.21	0.65±0.19	0.02	0.487	0.61±0.21	0.64±0.22	-0.03	0.173
Posterior								
Total Mass (kg)	2.93±0.39	3.07±0.43	-0.13	0.106	2.98±0.45	2.96±0.45	0.02	0.647
Lean Mass (kg)	1.90±0.19	2.02±0.21	-0.13	0.036[a]	1.98±0.24	1.97±0.28	0.01	0.844
Fat Mass (kg)	0.97±0.29	0.97±0.29	0.00	0.913	0.93±0.29	0.92±0.28	0.02	0.405

Abbreviations: ACLR, anterior cruciate ligament reconstruction group; INV, involved leg; NINV, non-involved leg; CON, control group. [a] Primary outcome significant at p<0.05.

Table 2. Mean (±SD) Isokinetic Dynamometry Measures for Matched vs. Contralateral Legs of ACLR and Control Groups

Measures	Within-Group						Between-Group	
	ACLR			CON			ACLR vs. CON	
	INV	NINV	*p*-value (within ACLR)	Matched	Contralateral	*p*-value (within CON)	*p*-value (INV vs. Matched)	*p*-value (NINV vs. Contralateral)
Extension								
60°/sec (Nm/kg)	1.36±0.31	1.71±0.36	<0.001[a]	1.77±0.40	1.72±0.32	0.5645	0.0097[a]	0.9277
120°/sec (Nm/kg)	1.06±0.27	1.24±0.33	0.0028[b]	1.36±0.32	1.35±0.23	0.8922	0.0194	0.3599
Flexion								
60°/sec (Nm/kg)	0.97±0.19	1.04±0.15	0.0218[a]	1.05±0.17	1.01±0.20	0.1659	0.3722	0.7439
120°/sec (Nm/kg)	0.71±0.23	0.75±0.18	0.1663	0.81±0.16	0.74±0.14	0.0100	0.2471	0.8693

Abbreviations: ACLR, anterior cruciate ligament reconstruction group; CON, control group; INV, involved leg; NINV, non-involved leg. [a] Primary outcome significant at $p<0.05$. [b] Secondary outcome significant at $p<0.007$.

Table 3. Mean (±SD) Between-Leg Squat Jump Comparisons Within and Between ACLR and Control Groups

Measures	Within-Group						Between-Group	
	ACLR			CON			ACLR vs. CON	
	INV	NINV	*p*-value (within ACLR)	Matched Leg	Contralateral Leg	*p*-value (within CON)	*p*-value (INV vs. Matched)	*p*-value (NINV vs. Contralateral)
Peak Force (N)	296±45	375±55	0.0004[a]	372±88	365±87	0.5907	0.0152[a]	0.7364
RFD (avg.) (N/s)	1059±406	1164±368	0.2345	1422±725	1356±686.3	0.1575	0.1695	0.3814
RFD (peak) (N/s)	2499±723	2512±573	0.9531	3368±1366	3669±1919	0.3973	0.0797	0.0820
S-Gradient (N/s)	1367±767	1880±888	0.0346	1971±856	2043±1030	0.6736	0.0793	0.6969
A-Gradient (N/s)	1049±324	1134±315	0.3960	1591±1081	1364±866	0.0307	0.1150	0.3768

Abbreviations: ACLR, anterior cruciate ligament reconstruction group; CON, control group; INV, involved leg; NINV, non-involved leg; RFD (avg.), average rate of force development; RFD (peak), peak rate of force development; S-Gradient, starting gradient; A-Gradient, acceleration gradient.

Note: Between-group comparisons made between ACLR INV leg vs. CON Matched leg, ACLR NINV leg vs. CON Contralateral leg.

[a] Primary outcome significant at $p<0.05$.

Table 4. Mean (±SD) Double Leg Squat Jump Measures Between ACLR and Control Groups

Measures	**ACLR**	**CON**	**Mean Difference**	***p*-value**
Peak Force (N)	664±78	726±164	-61.9	0.2414
RFD (avg.) (N/s)	2182±677	2670±1363	-487.8	0.2839
RFD (peak) (N/s)	4393±1087	6572±2995	-2179.1	0.0422
S-Gradient (N/s)	3015±1329	3915±1755	-899.5	0.1791
A-Gradient (N/s)	2131±479	2757±1763	-626.5	0.2660
Jump Height (m)	0.24±0.07	0.26±0.07	-0.02	0.4450
Jump Height Ratio	0.47±0.25	1.23±0.76	0.76	0.0053[b]

Abbreviations: ACLR, anterior cruciate ligament reconstruction group; CON, control group; RFD (avg.), average rate of force development; RFD (peak), peak rate of force development; S-Gradient, starting gradient; A-Gradient, acceleration gradient.

[a] Primary outcome significant at $p<0.05$.

[b] Secondary outcome significant at $p<0.007$.

Figures

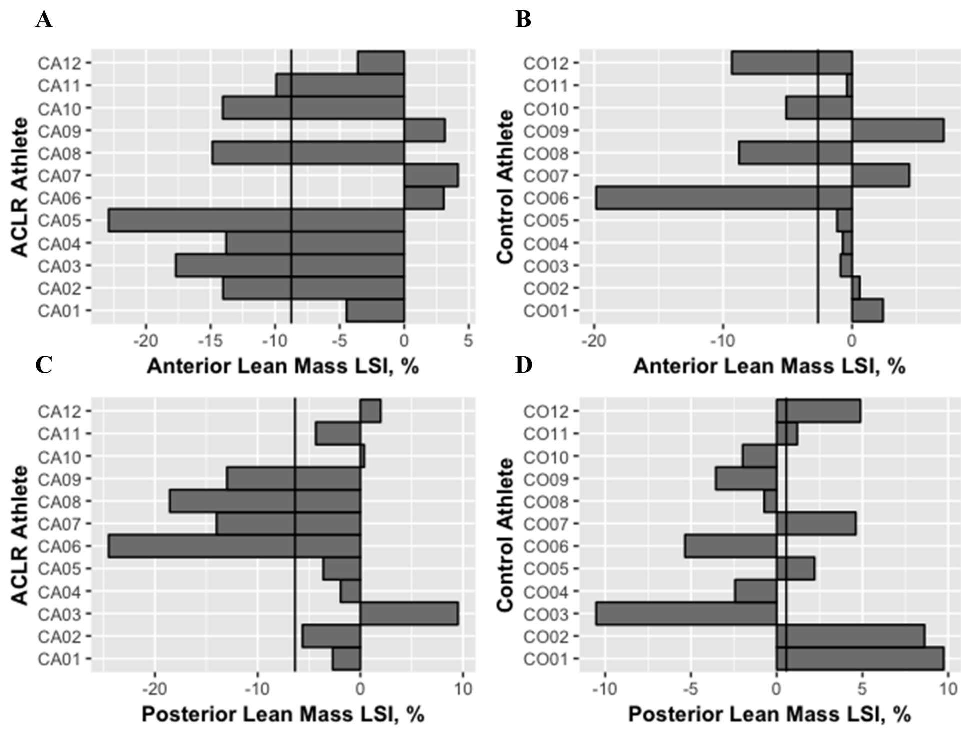

Figure 1. Anterior (Panels A&B) and Posterior (Panels C&D) Compartmental Limb Symmetry Index Calculations for Each ACLR and Control Athlete

Note: Each ACLR athlete and individually-matched control are represented on the same row. The solid black vertical line on each panel represents the mean limb symmetry index for each respective region.

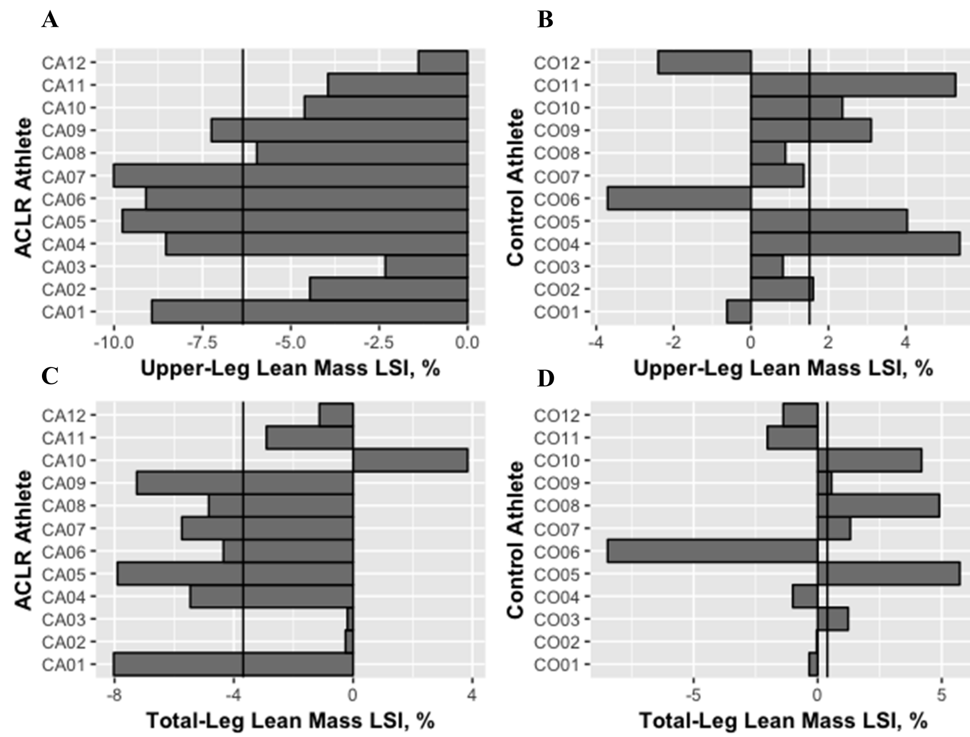

Figure 2. Upper-leg (Panels A&B) and Total-leg (Panels C&D) Limb Symmetry Index Calculations for Each ACLR and Control Athlete

Note: Each ACLR athlete and individually-matched control are represented on the same row. The solid black vertical line on each panel represents the mean limb symmetry index for each respective region.

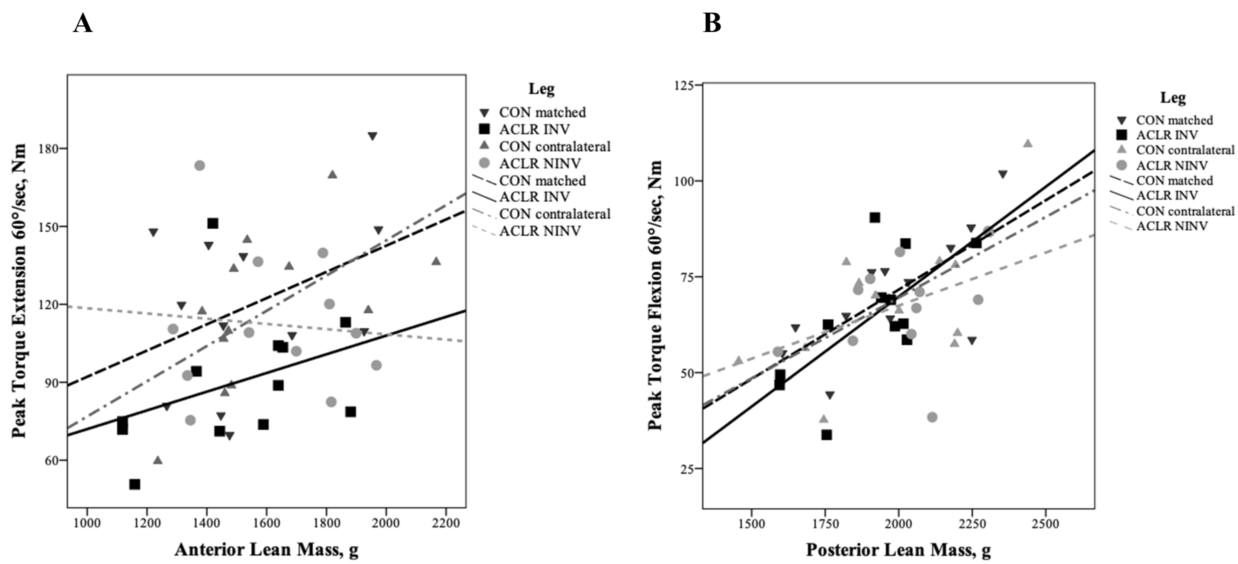

Figure 3. Relationship of Compartmental Lean Mass and Isokinetic Peak Torque in the ACLR Group's Involved (INV) and Non-Involved (NINV) Legs and in the Control Group's Matched and Contralateral Legs During Extension at 60°/sec (Panel A) and Flexion at 60°/sec (Panel B)

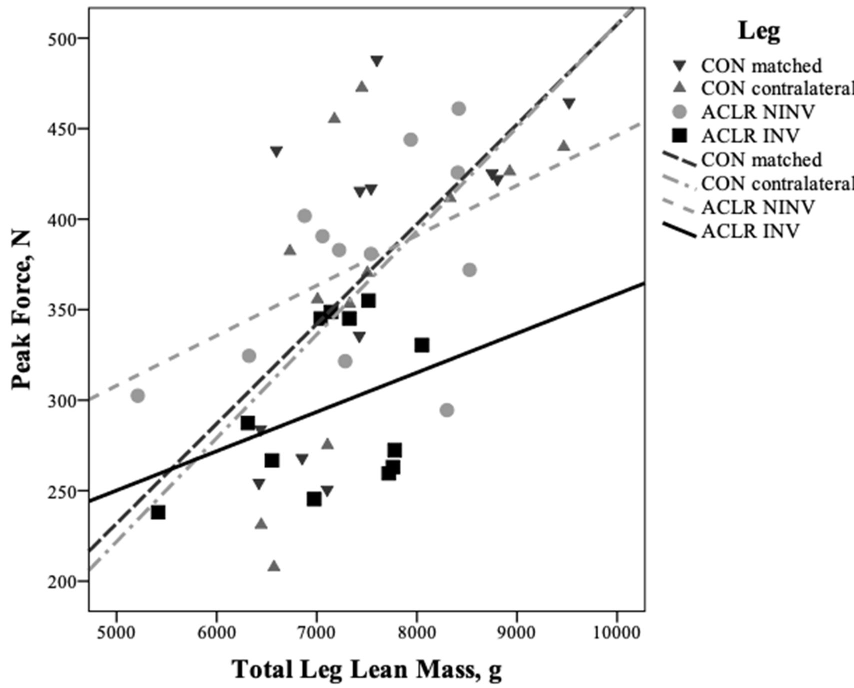

Figure 4. Relationship of Total-leg Lean Mass and Peak Force Produced During the Squat Jump in the ACLR Group's Involved (INV) and Non-Involved (NINV) Legs and in the Control Group's Matched and Contralateral Legs

CHAPTER 6. CONCLUSION

Research Results and Implications

While muscle function assessments have commonly been used within the sport performance and rehabilitation settings to monitor athletes' training and rehabilitation progress, lower extremity lean mass has been more recently evaluated for this purpose. However, most current literature has reported examining these measures independently. Additionally, few studies have examined the relationship between *asymmetries* in contralateral lean mass and muscle function—despite the utility that examining this association may have for lower extremity injury risk assessment. This dissertation offered a more detailed understanding of the relationship between leg lean mass and muscle function via utilization of a novel lateral DXA scanning method for quantifying upper-leg compartmental lean mass. Observations demonstrated the importance of examining contralateral and ipsilateral upper-leg lean mass asymmetries, using DXA, in relation to strength/force, allowing for a more detailed analysis of relative muscle functionality.

First, the agreement of the lateral DXA scanning method compared to the standard total-body frontal DXA scanning method was assessed on a Hologic Horizon A scanner. While this method previously demonstrated accuracy in quantifying lower extremity body composition compared to measurements of equal area in the standard frontal view when using a GE Lunar iDXA (Raymond et al., 2017), this dissertation's first study did not observe agreement between lateral and frontal view measurements when using the Hologic Horizon A scanner. These observations cautioned use of this scanner when examining leg composition in the lateral view—limiting the feasibility of performing this measurement method on DXA scanner models made by different manufacturers. Therefore, observations warranted the GE Lunar iDXA's exclusive use for this dissertation's subsequent studies.

Second, in a healthy collegiate athlete sample, the association between lateral view upper-leg compartmental (i.e., anterior/posterior) lean mass and muscle-specific and explosive strength were assessed. Further, these relationships were compared to associations observed between the preceding strength/force measures and total- and upper-leg lean mass measured in the frontal DXA scanning view. Observations indicated moderate-to-strong relationships between anterior and posterior upper-leg lean mass and (a) isokinetic extensor and flexor peak torque, respectively, and (b) squat jump height and force production. These lateral view associations were similar in strength to those observed in the frontal scanning view. Observations indicated the feasibility of utilizing the lateral segmentation method to more comprehensively assess relationships between lean mass in smaller ROIs and muscle-specific and explosive strength—assessments offering utility in examining asymmetries possibly increasing athletes' injury risk.

Finally, in a matched case-control study, differences in lean mass and muscle-specific and explosive strength between (a) the involved and non-involved legs of ACLR adolescent female athletes one-year post-reconstruction and (b) matched legs of ACLR and control athletes were examined. Further, relationships between (a) compartmental lean mass versus isokinetic peak torque and (b) total-leg lean mass versus squat jump force production were assessed. Observations revealed significant deficits in lean mass, isokinetic extensor peak torque, and squat jump force production in the ACLR involved leg, in addition to lower extensor peak torque and force produced per unit of lean mass in

ACLR athletes' legs versus matched controls. These observations indicated significant muscle dysfunction in both ACLR athletes' legs. This investigation also provided a more in-depth analysis of location-specific deficits in this population—important for clinicians to consider when designing and modifying individualized training and rehabilitation programs to reduce lean mass and functional asymmetries, perhaps decreasing secondary ACL injury risk.

This dissertation established that leg lean mass measured using the lateral segmentation method on a GE Lunar iDXA can be used concurrently with muscle-specific strength (e.g., isokinetic dynamometry) and force production (i.e., jump mechanography) measurements to examine healthy and ACLR athletes' relative muscle functionality.

Future Research

Although this dissertation provided a more detailed analysis of DXA-measured lean mass's moderate-to-strong relationship with muscle-specific strength and force production, in addition to elucidating how ACLR athletes' involved leg lean mass deficits may impair muscle function, future studies should examine longitudinal changes in the relationship between lean mass and strength/force during athletes' training and rehabilitation programs. Presently, it is unknown how the association between lean mass and (a) isokinetic peak torque and (b) jump mechanography-derived force production change in response to training and rehabilitation. Further, as neuromuscular activation/control has demonstrated relationships with ACLR athletes' muscle dysfunction, future studies should examine ACLR athletes' contralateral and ipsilateral quadriceps and hamstring muscle activation during isokinetic and jump mechanography testing, allowing for assessment of the contribution of neuromuscular activation, in combination with lean mass, to performance.

CHAPTER 7. REFERENCES

Aagaard, P, Simonsen, EB, Trolle, M, Bangsbo, J, Klausen, K. Isokinetic hamstring/quadriceps strength ratio: Influence from joint angular velocity, gravity correction and contraction mode. Acta Physiol Scand. 1995;154:421-7.

Aagaard, P, Simonsen, EB, Bangsbo, J, and Klausen, K. Specificity of training velocity and training load gains on isokinetic knee joint strength. Acta Physiol Scand. 1996;156:123-9.

Aagaard, P, Thorstensson, A. Neuromuscular aspects of exercise—adaptive responses evoked by strength training. In: Textbook of Sport Medicine: Basic Science and Clinical Aspects of Sports Injury and Physical Activity. M Kjær, M Krogsgaard, P Magnusson, L Engebretsen, H Roos, T Takala, and SL, eds. Malden, MA: Blackwell, 2008. pp. 70–106.

Ackland, TR, Lohman, TG, Sundgot-Borgen, J, Maughan, RJ, Meyer, NL, Stewart, AD, and Muller, W. Current status of body composition assessment in sport. Sports Med. 2012;42:227-49.

Adams D, Logerstedt D, Hunter-Giordano A, Axe MJ, Snyder-Mackler L. Current concepts for anterior cruciate ligament reconstruction: a criterion-based rehabilitation progression. J Orthop Sports Phys Ther. 2012;42:601-14.

Akagi, R, Tohdoh, Y, Takahashi, H. Muscle strength and size balances between reciprocal muscle groups in the thigh and lower leg for young men. Int J Sports Med. 2012;33(5):386-9.

Akagi, R, Tohdoh, Y, Takahashi H. Strength and size ratios between reciprocal muscle groups in the thigh and lower leg of male collegiate soccer players. Clin Physiol Funct Imaging. 2014;34:121-5.

Alentorn-Geli, E, Myer, GD, Silvers, HJ, Samitier, G, Romero, D, Lázaro-Haro, C, Cugat, R. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. Knee Surg Sports Tramatol Arthrosc. 2009;17(7):705-29.

Alkjaer, T, Simonsen, EB, Magnusson, SP, Dyhre-Poulsen, P, Aagaard, P. Antagonist muscle moment is increased in ACL deficient subjects during maximal dynamic knee extension. Knee. 2012;19(5):633–9.

Andersen, JL, Lamb, SE, Barker, KL, Davies, S, Dodd, CA, Beard, DJ. Changes in muscle torque following anterior cruciate ligament reconstruction: A comparison between hamstrings and patella tendon graft procedures on 45 patients. Acta Orthop Scand. 2002;73(5):546-52.

Arangio, GA, Chen, C, Kalady, M, Reed, JF. Thigh muscle size and strength after anterior cruciate ligament reconstruction and rehabilitation. Journal of Orthopaedic & Sports Physical Therapy. 1997;26(5):238-43.

Ardern, CL, Glasgow, P, Schneiders, A, et al. Consensus statement on return to sport from the First World Congress in Sports Physical Therapy, Bern. Br J Sports Med. 2016;50(14), 853-64.

Ardern CL, Taylor NF, Feller JA, Webster KE. A systematic review of the psychological factors associated with returning to sport following injury. *Br J Sports Med*. 2013;47(17):1120-6.

Baltzopoulos, V, Brodie, DA. Isokinetic dynamometry. Sports Med. 1989;8(2):101-116.

Baltzopoulos, B, King, M, Gleeson, N, De Ste Croix, M. The BASES expert statement on measurement of muscle strength with isokinetic dynamometry. Sport and Exercise Science. 2012;31:12-13.

Barlow, MJ, Oldroyd, B, Smith, D, Lees, MJ, Brightmore, A, Till, K, Jones, B, Hind, K. Precision error in dual-energy X-ray absorptiometry body composition measurements in elite male rugby league players. J Clin Densitom. 2015;18(4):546-50.

Baugher, WH, Warren, RF, Marshall, JL, Joseph, A. Quadriceps atrophy in the anterior cruciate insufficient knee. Am J Sports Med. 1984;12:192-5.

Bazzocchi, A, Ponti, F, Albisinni, U, Battista, G, Guglielmi, G. DXA: Technical aspects and application. Eur J Radiol. 2016;85:1481-92.

Bell, DR, Sanfilippo, JL, Binkley, N, Heiderscheit, BB. Lean mass asymmetry influences force and power asymmetry during jumping in collegiate athletes. J Strength Cond Res. 2014;28(4):884-91.

Beynnon, BD, Vacek, PM, Newell, MK, Tourville, TW, Smith, HC, Shultz, SJ, Slauterbeck, JR, Johnson, RJ. The effects of level of competition, sport, and sex on the incidence of first-time noncontact anterior cruciate ligament injury. Am J Sports Med. 2014;42(8):1806-12.

Bilsborough, JC, Greenway, K, Opar, D, Livingstone, S, Cordy, J, Coutts, AJ. The accuracy and precision of DXA for assessing body composition in team sport athletes. J Sports Sci. 2014;32(19):1821-8.

Bishop, C, Turner, A, Read, P. Effects of inter-limb asymmetries on physical and sports performance: A systematic review. J Sports Sci. 2018;36(10):1135-44.

Bloms, LP, Fitzgerald, JS, Short, MW, and Whitehead, JR. The effects of caffeine on vertical jump height and execution in collegiate athletes. J Strength Cond Res. 2016;30:1855-1861.

Bobbert, MF, Gerritsen, KG, Litjens, MC, Van Soest, AJ. Why is countermovement jump height greater than squat jump height? Med Sci Sports Exerc. 1996;28(11):1402-12.

Borchers, J. R., Pedroza, A., & Kaeding, C. Activity level and graft type as risk factors for anterior cruciate ligament graft failure: a case-control study. The Am J Sports Med. 2009;37(12), 2362-7.

Boden BP, Dean GS, Feagin JA, Garrett WE. Mechanisms of anterior cruciate ligament injury. Orthopedics. 2000;23:573–8.

Bosch TA, Burruss TP, Weir NL, Fielding KA, Engel BE, Weston TD, Dengel DR. Abdominal body composition difference in NFL football players. J Strength Cond Res. 2014;28(12):3313-9.

Bosch, TA, Carbuhn, A, Stanforth, PR, Oliver, JM, Keller, KA, Dengel, DR. Body composition and bone mineral density of Division I collegiate football players, a Consortium of College Athlete Research (C-CAR) study. J Strength Cond Res. 2018. doi: 10.1519/JSC.0000000000001888.

Bosch TA, Steinberger J, Sinaiko AR, Moran A, Jacobs DR, Kelly AS, Dengel DR. Identification of sex-specific thresholds for accumulation of visceral adipose tissue in adults. Obesity. 2015;23(2):375–82.

Bryant, AL, Kelly, J, Hohmann, E. Neuromuscular adaptations and correlates of knee functionality following ACL reconstruction. J Orthop Res. 2008;26:126-35.

Buehring, B, Krueger, D, Libber, J, Heiderscheit, B, Sanfilippo, J, Johnson, B, Binkley, N. Dual-energy X-ray absorptiometry measured regional body composition least significant change: Effect of region of interest and gender in athletes. J Clin Densitom. 2014;17(1):121-8.

Burkhart, TA, Arthurs, KL, Andrews, DM. Manual segmentation of DXA scan images results in reliable upper and lower extremity soft and rigid tissue mass estimates. J Biomech. 2009;27(3):197-206.

Byrne, C, Eston, R. The effect of exercise-induced muscle damage on isometric and dynamic knee extensor strength and vertical jump performance. J Sports Sci. 2002;20(5):417-25.

Cardone, C, Menegassi, Z, Emygdio, R. Isokinetic assessment of muscle strength following anterior cruciate ligament reconstruction. Isokinet Exerc Sci. 2004;12(3):173-7.

Chappell, JD, Yu, B, Kikendall, DT, Garrett, WE. A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *Am J Sports Med.* 2002;30:261-7.

Cohen J. Statistical Power Analysis for the Behavioral Sciences. 2nd ed. Hillsdale (NJ): Lawrence Erlbaum Associates, 1988. pp. 567.

Cormie, P, McBride, JM, McCaulley, GO. Power-time, force-time, and velocity-time curve analysis of the countermovement jump: Impact of training. J Strength Cond Res. 2009;23(1):177-86.

Croisier, JL, Forthomme, B, Namurois, M. H, Vanderthommen, M, and Crielaard, JM. Hamstring muscle strain recurrence and strength performance disorders. Am J Sports Med. 2002;30:199-203.

Cronin, JB, Hansen, KT. Strength and power predictors of sports speed. J Strength Cond Res. 2005;19(2):349-57.

Davies, GJ, Riemann, B, Ellenbecker, T. Role of isokinetic testing and training after ACL injury and reconstruction. In: Noyes F, Barber-Westin S (eds) ACL Injuries in the Female Athlete (pp. 567-588). Berlin, Heidelberg: Springer; 2018.

Denadai, BS, Oliveira, FBD, Camarda, SRDA, Ribeiro, L, and Greco, CC. Hamstrings-to-quadriceps strength and size ratios of male professional soccer players with muscle imbalance. Clin Physiol Funct Imaging. 2016;36:159-64.

Dengel, DR, Raymond, CR, Bosch, TA. Assessment of Muscle Mass. In: Lukaski, HC (ed.). Body Composition: Health and Performance in Exercise and Sport. Boca Raton, FL: CRC Press; 2017:27-47.

Eagles, AN, Sayers, MGL, Bousson, M, Lovell, DI. Current methodologies and implications of phase identification of the vertical jump: A systematic review and meta-analysis. Sports Med. 2015;45(9):1311-23.

Feiring, DC, Ellenbecker, TS, and Derscheid, GL. Test-retest reliability of the Biodex isokinetic dynamometer. J Orthop Sports Phys Ther. 1990;11:298-300.

Fitzgerald, JS, Johnson, L, Tomkinson, G, Stein, J, Roemmich, JN. Test-retest reliability of jump execution variables using mechanography: A comparison of jump protocols. J Sports Sci. 2017:36(9):963-9.

Ford, KR, Myer, GD, Hewett, TE. Reliability of dynamic knee motion in female athletes. Paper presented at: American Society of Biomechanics Annual Meeting; December 25, 2003; Toledo, Ohio.

Ford, KR, Myer, GD, Hewett, TE. Valgus knee motion during landing in high school female and male basketball players. Med Sci Sports Exerc. 2003;35:1745-50.

Fukunaga, T, Miyatani, M, Tachi, M, Kouzaki, M, Kawakami, Y, and Kanehisa, H. Muscle volume is a major determinant of joint torque in humans. Acta Physiol. 2001;172:249-55.

GE Healthcare Lunar. enCORE-based X-ray Bone Densitometer: User Manual. Madison, WI: GE Healthcare, p. 59, 2013. Available from: www.gehealthcare.com.

Genton, L, Karsegard, VL, Zawadynski, S, Kyle, UG, Pichard, C, Golay, A, Hans, D. B. Comparison of body weight and composition measured by two different dual energy X-ray absorptiometry devices and three acquisition modes in obese women. Clin Nutr. 2005;25(3):428-37.

Glickman, SG, Marn, CS, Supiano, MA, Dengel, DR. Validity and reliability of dual-energy X-ray absorptiometry for the assessment of abdominal adiposity. J Appl Physiol. 2004;97:509-14.

Goerger, BM, Marshall, SW, Beutler, AI, Blackburn, JT, Wilckens, JH, Padua, DA. Anterior cruciate ligament injury alters preinjury lower extremity biomechanics in the injured and uninjured leg: The JUMP-ACL study. Br J Sports Med. 2015;49:188-95.

Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: The Delaware-Oslo ACL cohort study. Br J Sports Med. 2016;50(13):804-8.

Haarbo, J, Gotfredsen, A, Hassager, C, Christiansen, C. Validation of body composition by dual energy X-ray absorptiometry (DEXA). Clin Physiol. 1991;11(4):331-41.

Hairi, NN, Cumming, RG, Naganathan, V, et al. Loss of muscle strength, mass (sarcopenia), and quality (specific force) and its relationship with functional limitation and physical disability: The Concord Health and Ageing in Men Project. J Am Geriatr Soc. 2010;58(11):2055-62.

Halkjaer-Kristensen, J, Ingemann-Hansen, T. Wasting of the human quadriceps muscle after knee ligament injuries: II Muscle fiber morphology. Scand J Rehabil Med. 1985;13(Suppl):12-20.

Harridge, SD, Bottinelli, R, Canepari, M, Pellegrino, MA, Reggiani, C, Esbjornsson, M, and Saltin B. Whole-muscle and single fibre contractile properties and myosin heavy chain isoforms in humans. Pflugers Arch. 1996;432:913–20.

Hart, NH, Nimphius, S, Spiteri, T, Cochrane, JL, Newton, RU. Segmental musculoskeletal examinations using dual-energy X-ray absorptiometry (DXA): Positioning and analysis considerations. J Sports Sci Med. 2015;14:620-6.

Heijne, A, Werner, S. A 2-year follow-up of rehabilitation after ACL reconstruction using patellar tendon or hamstring tendon grafts: A prospective randomised outcome study. Knee Surg Sports Traumatol Arthrosc. 2010;18(6):805-13.

Hewett, TE. Neuromuscular and hormonal factors associated with knee injuries in female athletes: Strategies for intervention. Sports Med. 2000;29:313–27.

Hewett, TE, Ford, KR, Myer, GD. Anterior cruciate ligament injuries in female athletes: Part 2, a meta-analysis of neuromuscular interventions aimed at injury prevention. Am J Sports Med. 2006;34(3):490-8.

Hewett, TE, Myer, GD, Ford, KR. Anterior cruciate ligament injuries in female athletes: Part 1, mechanisms and risk factors. Am J Sports Med. 2006;34(2):299-311.

Hewett, TE, Myer, GD, Ford, KR, Heidt, RS, Colosimo, AJ, McLean, SG, Van den Bogert, AJ, Paterno, MV, Succop, P. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. Am J Sports Med. 2005;33(4):492-501.

Hewett TE, Myer GD, Ford KR, Paterno MV, Quatman CE. Mechanisms, prediction, and prevention of ACL injuries: cut risk with three sharpened and validated tools. J Orthop Res. 2016;34(11):1843-55.

Hewit, J, Cronin, J, Hume, P. Multidirectional leg asymmetry assessment in sport. Strength Cond J. 2012;34(1):82-6.

Holsgaard-Larsen, A, Jensen, C, Mortensen, NHM, Aagaard, P. Concurrent assessments of lower limb loading patterns, mechanical muscle strength and functional performance in ACL-patients—A cross-sectional study. Knee. 2014;21(1):66-73.

Hopkins, WG, Marshall, SW, Batterham, AM, Hanin, J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009;41(1):3-12.

Hori N, Newton RU, Kwamori N, McGuigan MR, Kraemer WJ, and Nosaka K. Reliability of performance measurements derived from ground reaction force data during countermovement jump and the influence of sampling frequency. J Strength Cond Res. 2009;23:874-82.

Hull, H, He, Q, Thornton, J, Javed, F, Allen, L, Wang, J, Pierson, RN, Gallagher, D. iDXA, Prodigy, and DPXL dual-energy X-ray absorptiometry whole-body scans: A cross-calibration study. J Clin Densitom. 2009;12(1):95-102.

Impellizzeri, FM, Rampinini, E, Maffiuletti, N, and Marcora, SM. A vertical jump force test for assessing bilateral strength asymmetry in athletes. Med Sci Sports Exerc. 2007;39:2044-50.

Iossifidou, A, Baltzopoulos, V, and Giakas, G. Isokinetic knee extension and vertical jumping: Are they related? J Sports Sci. 2005;23:1121-27.

Ithurburn, MP, Paterno, MV, Ford, KR, Hewett TE, Schmitt LC. Young athletes with quadriceps femoris strength asymmetry at return to sport after anterior cruciate ligament reconstruction demonstrate asymmetric single-leg drop-landing mechanics. Am J Sports Med. 2015;43(11):2727-37.

Jordan, MJ, Aagaard, P, Herzog, W. Lower limb asymmetry in mechanical muscle function: A comparison between ski racers with and without ACL reconstruction. Scand J Med Sci Sports. 2015;25(3):e301-9.

Jorgensen, L, Jacobsen, BK. Changes in muscle mass, fat mass, and bone mineral content in the legs after stroke: A 1 year prospective study. Bone. 2001;28(60):655-9.

Joseph, AM, Collins, CL, Henke, NM, Yard, EE, Fields, SK., Comstock, RD. A multisport epidemiologic comparison of anterior cruciate ligament injuries in high school athletics. J Athl Train. 2013;48(6):810-7.

Kaul, S, Rothney, MP, Peters, DM, Wacker, WK, Davis, CE, Shapiro, MD, Ergun, DL. Dual-energy X-ray absorptiometry for quantification of visceral fat. Obesity. 2012;20(6):1313-8.

Kerr, A, Slater, GJ, Byrne, N, Nana, A. Reliability of 2 different positioning protocols for dual-energy X-ray absorptiometry measurement of body composition in healthy adults. J Clin Densitom. 2016;19(3):282-9.

Kim, J, Wang, Z, Heymsfield, SB, Baumgartner, RN, Gallagher, D. Total-body skeletal muscle mass: Estimation by a new dual-energy X-ray absorptiometry method. Am J Clin Nutr. 2002;76:378-83.

Konishi, Y, Fukubayashi, T, Takeshita, D. Possible mechanism of quadriceps femoris weakness in patients with ruptured anterior cruciate ligament. Med Sci Sports Exerc. 2002;34:1414-18.

Konishi, Y, Ikeda, K, Nishino, A, Sunaga, M, Aihara, Y, Fukubayashi, T. Relationship between quadriceps femoris muscle volume and muscle torque after anterior cruciate ligament repair. Scand J Med Sci Sports. 2007;17(6):656–61.

Konishi, Y, Konishi, H, Fukubayashi, T. Gamma loop dysfunction in quadriceps on the contralateral side in patients with ruptured anterior cruciate ligament. Med Sci Sports Exerc. 2003;35:897-900.

Konishi, Y, Oda, T, Tsukazaki, S, Kinugasa, R, Hirose, N, Fukubayashi, T. Relationship between quadriceps femoris muscle volume and muscle torque after anterior cruciate ligament rupture. Knee Surg Sports Traumatol Arthrosc. 2011;19(4):641-5.

Konishi, Y, Oda, T, Tsukazaki, S, Kinugasa, R, Fukubayashi, T. Relationship between quadriceps femoris muscle volume and muscle torque at least 18 months after anterior cruciate ligament reconstruction. Scand J Med Sci Sports. 2012;22(6):791-6.

Krzykala, M, Leszczynski, P. Asymmetry in body composition in female hockey players. Homo. 2015;66(4):379-86.

Kuenze, CM, Blemker, SS, Hart, JM. Quadriceps function relates to muscle size following ACL reconstruction. J Orthop Res. 2016;34(9):1656-62.

Kuenze CM, Hertel J, Hart JM. Quadriceps muscle function after exercise in men and women with a history of anterior cruciate ligament reconstruction. J Athl Train. 2014;49:740-6.

Kvist, J. Rehabilitation following anterior cruciate ligament injury. Sports Med. 2004;34(4):269-80.

Kweon, C, Lederman, ES, & Chabra, A. Anatomy and biomechanics of the cruciate ligaments and their surgical implications. In: The Multiple Ligament Injured Knee (pp. 17-27). New York, NY: Springer; 2013.

Lambrinoudaki, I, Georgiou, E, Douskas, G, Tsekes, G, Kyriakidis, M, Proukakis, C. Body composition assessment by dual-energy X-ray absorptiometry: Comparison of prone and supine measurements. Metabolism. 1998;47(11):1379-82.

Lee, SY, Gallagher, D. Assessment methods in human body composition. Curr Opin Clin Nutr Metab Care. 2008;11:566-72.

Lees, A, Vanrenterghem, J, De Clercq, D. The maximal and submaximal vertical jump: implications for strength and conditioning. J Strength Cond Res. 2004;18:787–91.

Lepley, LK. Deficits in quadriceps strength and patient-oriented outcomes at return to activity after ACL reconstruction: A review of the current literature. Sports Health. 2015;7(3):231-8.

Lepley, LK, Lepley, AS, Onate, JA, Grooms, DR. Eccentric exercise to enhance neuromuscular control. Sports Health. 2017;9(4):333-40.

Lewiecki, EM. Clinical applications of bone density testing for osteoporosis. Minerva Med. 2005;96(5):317-30.

Leys, T, Salmon, L, Waller, A, Linklater, J, Pinczewski, L. Clinical results and risk factors for reinjury 15 years after anterior cruciate ligament reconstruction: A prospective study of hamstring and patellar tendon grafts. Am J Sports Med. 2012;40(3):595-605.

Li, G. Rudy, TW, Sakane, M, Kanamori, A, Ma, CV, Woo, SY. The importance of quadriceps and hamstring muscle loading on knee kinematics and in-situ forces in the ACL. J Biomech. 1999;32:395-400.

Lohman, M, Tallroth, K, Kettunen, JA, Marttinen, MT. Reproducibility of dual-energy x-ray absorptiometry total and regional body composition measurements using different scanning positions and definitions of regions. Metabolism. 2009;58(11):1663-8.

Lohmander, LS, Englund, PM, Dahl, LL, Roos, EM. The long-term consequence of anterior cruciate ligament and meniscus injuries: Osteoarthritis. Am J Sports Med. 2007;35:1756–69.

Markolf, KL, Graff-Radofrd, A, Amstutz, HC. In vivo knee stability: A quantitative assessment using an instrumented clinical testing apparatus. *J Bone Joint Surg Am.* 1978;60:664-74.

Markovic, G, Diszar, D, Jukic, I, Cardinale, M. Reliability and factorial validity of squat and countermovement jump tests. J Strength Cond Res. 2004;18:551-5.

Masuda, K, Kikuhara, N, Takahashi, H, and Yamanaka, K. The relationship between muscle cross-sectional area and strength in various isokinetic movements among soccer players. J Sports Sci. 2003;21:851–8.

Mazess, RB, Barden, HS, Bisek, JP, Hanson, J. Dual-energy X-ray absorptiometry for total-body and regional bone-mineral and soft-tissue composition. Am J Clin Nutr. 1990;51:1106-12.

McHugh, MP, Tyler, TF, Browne, MG, Gleim, GW, Nicholas, SJ. Electromyographic predictors of residual quadriceps muscle weakness after anterior cruciate ligament reconstruction. Am J Sports Med. 2002;30(3):334-9.

McNair PJ, Marshall RN, Matheson JA. Important features associated with acute anterior cruciate ligament injury. N Z Med J. 1990;103:537-9.

Modica, MJ, Kanal, KM, Gunn, ML. The obese emergency patient: Imaging challenges and solutions. Radiographics. 2011;31:811-23.

Moir, GL, Garcia, A, Dwyer, GB. Intersession reliability of kinematic and kinetic variables during vertical jumps in men and women. Int Journal Sports Physiol Perform. 2009;4:317-30.

Montgomery, MM, Shultz, SJ, Schmitz, RJ, Wideman, L, Henson, RA. Influence of lean body mass and strength on landing energetics. Med Sci Sports Exerc. 2012;44:2376–83.

Murphy, DF, Connolly, DDAJ, Beynnon, BD. Risk factors for lower extremity injury: A review of the literature. Br J Sports Med. 2003;37(1):13-29.

Nana, A, Slater, GJ, Stewart, AD, Burke, LM. Methodology review: Using dual-energy X-ray absorptiometry (DXA) for the assessment of body composition in athletes and active people. Int J Sport Nutr Exerc Metab. 2014;24:198-215.

Neeter, C, Gustavsson, A, Thomee, P, et al. Development of a strength test battery for evaluating leg muscle power after anterior cruciate ligament injury and reconstruction. Knee Surg Sports Traumatol Arthrosc. 2006;14:571-80.

Newton, RU, Gerber, A, Nimphius, S, Shim, JK. Determination of functional strength imbalance of the lower extremities. J Strength Cond Res. 2006;20(4):971-7.

Olsen, OE, Myklebust, G, Engebretsen, L, Bahr, R. Injury mechanisms for anterior cruciate ligament injuries in team handball: A systematic video analysis. J Strength Cond Res. 2004;25(8):2151-60.

Osternig, LR, Caster, BL, James, CR. Contralateral hamstring (biceps femoris) coactivation patterns and anterior cruciate ligament dysfunction. Med Sci Sports Exerc. 1995;27:805-8.

Palmieri-Smith, RM, Lepley, LK. Quadriceps strength asymmetry after anterior cruciate ligament reconstruction alters knee joint biomechanics and functional performance at time of return to activity. Am J Sports Med. 2015;43(7):1662-69.

Palmieri-Smith, RM, Thomas, AC, Wojtys, EM. Maximizing quadriceps strength after ACL reconstruction. Clin Sports Med. 2008;27(3):405-24.

Paterno, MV, Ford, KR, Myer, GD, Heyl, R, Hewett, TE. Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. Clin J Sports Med. 2007;17(4):258-62.

Paterno, MV, Rauh, MJ, Schmitt, LC, Ford, KR, Hewett, TE. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. Clin J Sports Med. 2012;22(2):116–21.

Paterno, MV, Rauh, M, Thomas, S, Hewett, TE, Schmitt, L. Current return to sport criteria after ACL reconstruction fail to identify increased risk of second ACL injury in young athletes. Ortho J Sports Med. 2018;6(7_suppl 4). doi:10.1177/2325967118S00060.

Paterno, MV, Schmitt, LC, Ford, KR, Rauh, MJ, Huang, B, Hewett, TE. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. Am J Sports Med. 2010;38:1968-78.

Paterno, MV, Schmitt, LC, Ford, KR, Rauh, MJ, Myer, GD, Hewett, TE. Effects of sex on compensatory landing strategies upon return to sport after anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2011;41(8):553-9.

Pineau, JC, Filliard, JR, Bocquet, M. Ultrasound techniques applied to body fat measurement in male and female athletes. J Athl Train. 2009;44(2):142-7.

Pua, YH, Bryant, AL, Steele, JR, Newton, RU, Wrigley, TV. Isokinetic dynamometry in anterior cruciate ligament injury and reconstruction. Ann Acad Med Singapore. 2008;37(4):330–40.

Raymond, CJ, Bosch, TA, Busch, FK, Chow, LS, Dengel DR. Accuracy and reliability of assessing lateral compartmental leg composition using DXA. Med Sci Sports Exerc. 2017;49(4):833-9.

Raymond-Pope, CJ, Dengel, DR, Fitzgerald, JS, Bosch, TA. Association of compartmental leg lean mass measured by dual X-ray absorptiometry with force production. J Strength Cond Res. 2018. https://doi.org/10.1519/JSC.0000000000002688.

Renstrom, P, Ljungqvist, A, Arendt, E, et al. Non-contact ACL injuries in female athletes: An International Olympic Committee current concepts statement. Br J Sports Med. 2008;42(6):394-412.

Risberg, MA, Holm, I. The long-term effect of 2 postoperative rehabilitation programs after anterior cruciate ligament reconstruction: A randomized controlled clinical trial with 2 years of follow-up. Am J Sports Med. 2009;37(10):1958-66.

Roos, KG, Marshall, SW, Kerr, ZY, Golightly, YM, Kucera, KL, Myers, JB, Comstock, RD. Epidemiology of overuse injuries in collegiate and high school athletics in the United States. Am J Sports Med. 2015;43(7):1790-7.

Santos, DA, Silva, AM, Matias, CN, Fields, DA, Heymsfield, SB, Sardinha, LB. Accuracy of DXA in estimating body composition changes in elite athletes using a four compartment model as the reference method. Nutrition & Metabolism. 2010;7(22):7075-77.

Schantz, P, Randall-Fox, E, Hutchison, W, Tydén, A, Åstrand, PO. Muscle fibre type distribution, muscle cross-sectional area and maximal voluntary strength in humans. Acta Physiol Scand. 1983;117(2):219-26.

Schmitt, LC, Paterno, MV, Hewett, TE. The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2012;42(9):750-9.

Shultz, SJ, Pye, ML, Montgomery, MM, Schmitz, RJ. Association between lower extremity lean muscle mass and multiplanar knee laxity and stiffness: A potential explanation for sex differences in frontal and transverse plane knee laxity. Am J Sports Med. 2012;40:2836-44.

Shultz, SJ, Schmitz, RJ. Current Understandings and Directions for Future Research. In: Noyes F., Barber-Westin S. (eds.) ACL Injuries in the Female Athlete. Berlin, Heidelberg: Springer; 2018.

Shultz, SJ, Schmitz, RJ, Benjaminse, A, Collins, M, Ford, K, Kulas, AS. ACL Research Retreat VII: An Update on Anterior Cruciate Ligament Injury Risk Factor Identification, Screening, and Prevention: March 19–21, 2015; Greensboro, NC. J Athl Train. 2015;50(10):1076-93.

Silvers, HJ, Mandelbaum, BR. Prevention of anterior cruciate ligament injury in the female athlete. Br J Sports Med. 2007;41(suppl 1):i52-i59.

Slater, GJ, O'Connor, HT, Pelly, FE. Physique Assessment of Athletes. In: Driskell, JA, Wolinsky, I (eds). Nutritional Assessment of Athletes (2nd Ed). Boca Raton, FL: CRC Press; 2011:73-109.

Snyder-Mackler, L, DeLuca, PF, Williams, PR, Eastlack, ME, Bartolozzi, AR 3rd. Reflex inhibition of the quadriceps femoris muscle after injury or reconstruction of the anterior cruciate ligament. J Bone Joint Surg Am. 1994;76:555-60.

Sonesson S, Kvist J, Ardern C, Österberg A, Silbernagel KG. Psychological factors are important to return to pre-injury sport activity after anterior cruciate ligament reconstruction: Expect and motivate to satisfy. Knee Surg Sports Traumatol Arthrosc. 2017;25(5):1375-84.

Soriano, JMP, Ioannidou, E, Wang, J, Thornton, JC, Horlick, MN, Gallagher, D, Pierson Jr, RN. Pencil-beam vs fan-beam dual-energy X-ray absorptiometry comparisons across four systems: body composition and bone mineral. J Clin Densitom. 2004;7(3):281-9.

Stanforth, PR, Crim, BN, Stanforth, D, Stults-Kolehmainen, MA. Body composition changes among female NCAA division 1 athletes across the competitive season and over a multiyear time frame. J Strength Cond Res. 2014;28(2):300-7.

Stephenson ML, Smith DT, Heinbaugh EM, Moynes RC, Rockey SS, Thomas JJ, Dai B. Total and lower extremity lean mass percentage positively correlates with jump performance. J Strength Cond Res. 2015;29:2167-75.

Stewart, AD. Assessing body composition in athletes. Nutrition. 2001;17(7):694-5.

Stewart, AD, Sutton, L. (Eds.). Body Composition in Sport, Exercise and Health. New York, NY: Routledge; 2012.

Stackhouse, SK, Dean, JC, Lee, SC, Binder-MacLeod, SA. Measurement of central activation failure of the quadriceps femoris in healthy adults. Muscle Nerv Suppl. 2000;23(11):1706-12.

Thomas, AC, Wojtys, EM, Brandon, C, Palmieri-Smith, RM. Muscle atrophy contributes to quadriceps weakness after anterior cruciate ligament reconstruction. J Sci Med Sport. 2016;19(1):7-11.

Toombs, RJ, Ducher, G, Shepherd, JA, De Souza, MJ. The impact of recent technological advances on the trueness and precision of DXA to assess body composition. Obesity. 2012;20(1):30-9.

Tothill, P, Avenell, A, Love, J, Reid, DM. Comparisons between Hologic, Lunar and Norland dual-energy X-ray absorptiometers and other techniques used for whole-body soft tissue measurements. Eur J Clin Nutr. 1994;48(11):781-94.

Tothill, P, Avenell, A, Reid, DM. Precision and accuracy of measurements of whole-body bone mineral: Comparisons between Hologic, Lunar and Norland dual-energy X-ray absorptiometers. Br J Radiol. 1994;67(804):1210-7.

Tothill, P, Hannan, WJ, Wilkinson, S. Comparisons between a pencil beam and two fan beam dual energy X-ray absorptiometers used for measuring total body bone and soft tissue. Br J Radiol. 2001;74(878):166-76.

Uhorchak, JM, Scoville, CR, Williams, GN, Arciero, RA, Pierre, PS, Taylor, DC. Risk factors associated with noncontact injury of the anterior cruciate ligament. Am J Sports Med. 2003;31(6):831-42.

Urbach, D, Nebelung, W, Weiler, HT, Awiszus, F. Bilateral deficit of voluntary quadriceps muscle activation after unilateral ACL tear. Med Sci Sports Exerc. 1999;31(12):1691-6.

Van Loan, MD, Keim, NL, Berg, K, Mayclin, PL. Evaluation of body composition by dual energy x-ray absorptiometry and two different software packages. Med Sci Sports Exerc. 1995;27(4):587-91.

Walsh M, Boling MC, McGrath M, Blackburn JT, and Padua DA. Lower extremity muscle activation and knee flexion during a jump-landing task. J Athl Train. 2012;47:406–13.

Wellsandt, E, Failla, MJ, Snyder-Mackler, L. Limb symmetry indexes can overestimate knee function after anterior cruciate ligament injury. J Orthop Sports Ther. 2017;47(5):334-338.

White, KK, Lee, SS, Cutuk, A, Hargens, AR, Pedowitz, RA. EMG power spectra of intercollegiate athletes and anterior cruciate ligament injury risk in females. Med Sci Sports Exerc. 2003;35:371-6.

Wiggins, AJ, Grandhi, RK, Schneider, DK, Stanfield, D, Webster, KE, Myer, GD. Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. Am J Sports Med. 2016;44(7):1861-76.